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EXPERIMENTAL EVALUATION OF F-16 POLYCARBONATE CANOPY MATERIAL

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April 1981
Final Report for Period September 1978 - November 1980

MATERIAL LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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NOTICE

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER:

THEODORE NICHOLAS
Metals Behavior Branch
Metals and Ceramics Division

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Metals and Ceramics Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents a test program which was conducted to evaluate the relative merits and change in impact resistance of three coated monolithic polycarbonates, including initial production F-16 canopy material, and three laminated polycarbonates after being subjected to selected environmental exposure conditions. Environmental exposures which were investigated were: ultraviolet radiation, moisture, thermal, cont.

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sunlight, sunlight/moisture, combined temperature/humidity, and combined UV/humidity. To experimentally evaluate the influence of the exposure, samples of candidate materials were conditioned and subjected to the following tests: falling weight impact, high rate beam flexure, air cannon, flatwise tension, torsional shear, chemical craze, rain erosion, and abrasion.

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PREFACE

The effort documented in this report was performed by the University of Dayton Research Institute, Dayton (UDRI), Ohio, 45469, under Contract F33615-76-C-5124, entitled, "Response of Materials to Impulsive Loading," for the Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, 45433. Air Force administrative direction and technical support was provided by Dr. T. Nicholas, AFWAL/MLLN, Project Engineer. The active support of Mr. R. L. Peterson, AFWAL/FIEA, and Mr. D. Russell, ASD/YPEF, on this project is gratefully acknowledged for their comments, insights, and technical direction.

The work described herein was conducted during the period from September 1978 to November 1980. Project supervision was provided through the Experimental and Applied Mechanics Division of the University of Dayton Research Institute with Mr. G. Roth, Supervisor. Mr. Blaine S. West, Head, Applied Mechanics Group, Aerospace Mechanics Division, was the Project Engineer directing the overall activities. Technical effort was accomplished under Mr. K. I. Clayton as Principal Investigator responsible for the baseline environmental aging study on production coated polycarbonate, with Mr. J. F. Milholland responsible for the candidate coated monolithic specimen investigation and Mr. G. J. Stenger responsible for the candidate laminated specimen investigation. Conditioning was accomplished in the UDRI Nonmetallic Laboratory with R. Kuhbander and J. Stine being major contributors; accelerated outdoor exposure being subcontracted to the Desert Sunshine Exposure Test Laboratory, Arizona. Testing was conducted in the UDRI Structural Test Laboratory with E. C. Klein and P. E. Johnson being major contributors.

In addition, the authors wish to acknowledge the significant contributions of G. F. Schmitt, AFWAL/MLBE, C. J. Hurley, UDRI/

WPAFB, and Dr. J. Zahavi, AFWAL/MLBE Visiting Scientist, in successfully conducting an in-depth evaluation of the required rain erosion tests.

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SECTION I
INTRODUCTION

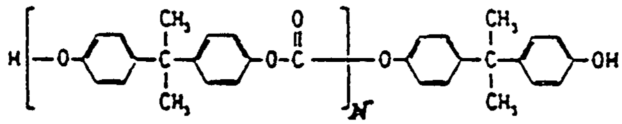
1. BACKGROUND

An increasing number of high performance Air Force aircraft are being fitted with transparencies utilizing polycarbonate (MIL-P-83310) material as the structural ply. This usage is dictated by the need to provide a transparency which can survive the impact energies associated with high speed birdstrike. The impact resistance of polycarbonate material is influenced by such parameters as thickness, temperature, ply configuration, processing procedure, surface finish, aging and environmental exposure. In some transparency designs, a single (monolithic) thick polycarbonate structural ply is used, especially when transparency deformations due to in-service loadings are required to remain small or when the number of ply interfaces is to be minimized for improved optics. The F-16 initial production canopy utilizes a coated monolithic polycarbonate transparency. In other applications, several thin polycarbonate and/or acrylic plies, separated by relatively low modulus interlayers, replace the monolithic construction. In either case, outer and inner surface protection of the polycarbonate may be provided by acrylic plies or protective coatings.

Historically, the impact resistance of polycarbonate and the resulting polycarbonate crew enclosure structures have been evaluated using material in the as-received condition. During in-service usage, the material is subjected to an environment that would be expected to cause degradation in impact resistance. Thus, from a practical standpoint, knowledge of the rate of degradation and the cumulative degradation at a given time is essential for evaluating the true capability of the transparency to perform its design function.

2. AGING CHARACTERISTICS OF UNCOATED POLYCARBONATE

A basic review of the manufacture and properties of polycarbonate is presented in Schnell.[1] Polycarbonate is produced by polycondensation of bisphenol A with phosgene and has the structure:



It is a polyester-type thermoplastic material having molecular weights in the range of 30,000 to 50,000 when formulated for processing by extrusion. This is the process used to form monolithic polycarbonate sheets.

As processed, polycarbonate is amorphous and does not have a sharp melting point. It begins to soften at the glass transition temperature, T_g, which is 147°C (297°F). Because it is noncrystalline, polycarbonate is attacked by a number of organic solvents. Although its stability to water is good for a polyester, it is attacked by moisture, particularly in combination with other environmental factors[2,3] such as U.V. radiation and heat. It is severely degraded by moisture during processing at elevated temperatures (220-230°C).[4,5]

Polycarbonate, as is the case with most other organic polymers, is sensitive to U.V. radiation and breaks down under

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(1) Schnell, H., Plast. Rubber Int., 2, 41 (1977).

(2) Davis, A., and Golden, J. H., J. Macromol. Sci.-C, 3, 49 (1969).

(3) Yamasaki, R. S., and Blaga, A., Mat. at Const., 10, 197 (1977).

(4) Long, T. S., and Sokol, R. J., Polymer Eng. Sci., 14, 817 (1974).

(5) Newcome, J., Plastics World, 42 (October 1977).

continuous U.V. exposure by a random chain scission process.[2,3] Molecular weight changes from 40-50,000 to 10,000 result from both long-term outdoor exposures and laboratory accelerated aging tests.[3]

Another important property of polycarbonate, also common to most organic polymers,[6] is that spontaneous physical aging can occur continuously on annealing at temperatures below T_g. This is a thermodynamic process which can be considered as a gradual low temperature continuation of vitrification which occurs initially around T_g. The rate of physical aging at 25°C (77°F) is slow but at higher temperatures closer to T_g it becomes more rapid. As stated in the literature, a general loss of ductility with time is associated with physical aging. Several examples of the embrittlement of polycarbonate due to aging are discussed in References (7-12). Broutman[11] postulates that cases of "field failures" of polycarbonate due to embrittlement may have resulted from stress relaxation due to physical aging rather than thermal or U.V. degradation.

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(2) Davis, A., and Golden, J. H., J. Macromol. Sci.-C, 3, 49 (1969).

(3) Yamasaki, R. S., and Blaga, A., Mat. at Const., 10, 197 (1977).

(6) Struik, L. C. E., Polymer Eng. Sci., 17, 165 (1977).

(7) Golden, J. H., Hammant, B. L., and Hazell, E. A., J. Appl. Polymer Sci., 11, 1571 (1967).

(8) Neki, K., and Geil, P. H., J. Macromol. Sci.-B, 8, 295 (1973).

(9) Allen, G., Morley, D. C. W., and Williams, T., J. Mat. Sci., 8, 1499 (1973).

(10) Adam, G. A., Cross, A., and Howard, R. N., J. Mat. Sci., 10, 1582 (1975).

(11) Broutman, L. J., and Krishnakumar, S. M., Polymer Eng. Sci., 16, 74 (1976).

(12) So, P., and Broutman, L. J., Polymer Eng. Sci., 16, 785 (1976).

3. PROGRAM OBJECTIVE

The objective of the program is to evaluate the relative merits and change in impact resistance of

(i) production F-16 coated monolithic polycarbonate, and

(ii) candidate F-16 coated monolithic and laminated polycarbonate canopy materials,

after being subjected to selected environmental exposure conditions.

4. SCOPE

Environmental exposures to be investigated were defined as follows: ultraviolet (UV) radiation, moisture, thermal, sunlight (EMMA), sunlight/moisture (EMMAQUA), combined temperature/humidity, and combined UV/humidity.

To experimentally evaluate the influence of the selected exposures, samples of coated monolithic and/or laminated polycarbonate were conditioned and subsequently subjected to tests, encompassing the following: falling weight impact (beam tests), MTS beam flexure tests at 2,000-inches per minute, air cannon tests, flatwise tension tests, torsional shear tests, chemical craze tests, rain erosion tests, and Bayer abrasion tests.

SECTION II

EXPERIMENTAL PROGRAM

A test program was conducted to qualitatively evaluate the material behavior of three coated monolithic polycarbonates and three laminated polycarbonates before and after exposure to selected environmental conditions. The following paragraphs describe the materials tested, test matrix, test specimen design/layout and fabrication, environmental conditioning of specimens, test procedure, and test results.

1. TEST MATERIALS

All test material was considered proprietary and was supplied by the Government. All material was furnished in flat sheet form and processed to be representative of material for production F-16 canopies.

The three vendors supplying coated monolithic polycarbonate material were identified as Vendor P, Vendor A, and Vendor B. For each, the base material consists of polycarbonate of nominal 0.75 inch thickness. Four coatings were utilized; Vendor P material being evaluated with two different coatings. The coated Vendor P material represents the initial production F-16 canopy material; having a different coating on each face. The C-254-1C coating is used on the outer surface of the aircraft transparency and the GR-212 coating is used on the aircraft transparency's inner surface. Vendor A material has its specific coating, and incorporates the same coating on both faces. Similarly, Vendor B material has its specific coating, and incorporates the same coating on both faces.

Three vendors, identified as Vendor E, Vendor F, and Vendor G, supplied laminated polycarbonate material consisting of one or more acrylic layers and one or more polycarbonate layers separated by relatively high compliance low modulus interlayers which provide the bonding between layers. For all candidate test laminates, the outer protection for the

polycarbonate was provided by an acrylic ply and inner protection was provided by an acrylic ply or a protective coating. Figure 1 shows the cross section of each laminated test material with corresponding typical thickness measurements.

2. TEST MATRIX

The required test matrix was developed to evaluate coated monolithic polycarbonate sheet material supplied from three different vendors and laminated polycarbonate sheet material supplied from three different vendors, before and after exposure to eight types of environmental conditioning.

The environmental conditioning consisted of:

(i) no conditioning (baseline),

(ii) ultraviolet light (UV),

(iii) moisture (95 percent R.H.),

(iv) thermal (120°F; 200°F),

(v) simultaneous elevated temperature and high relative humidity (temperature/humidity),

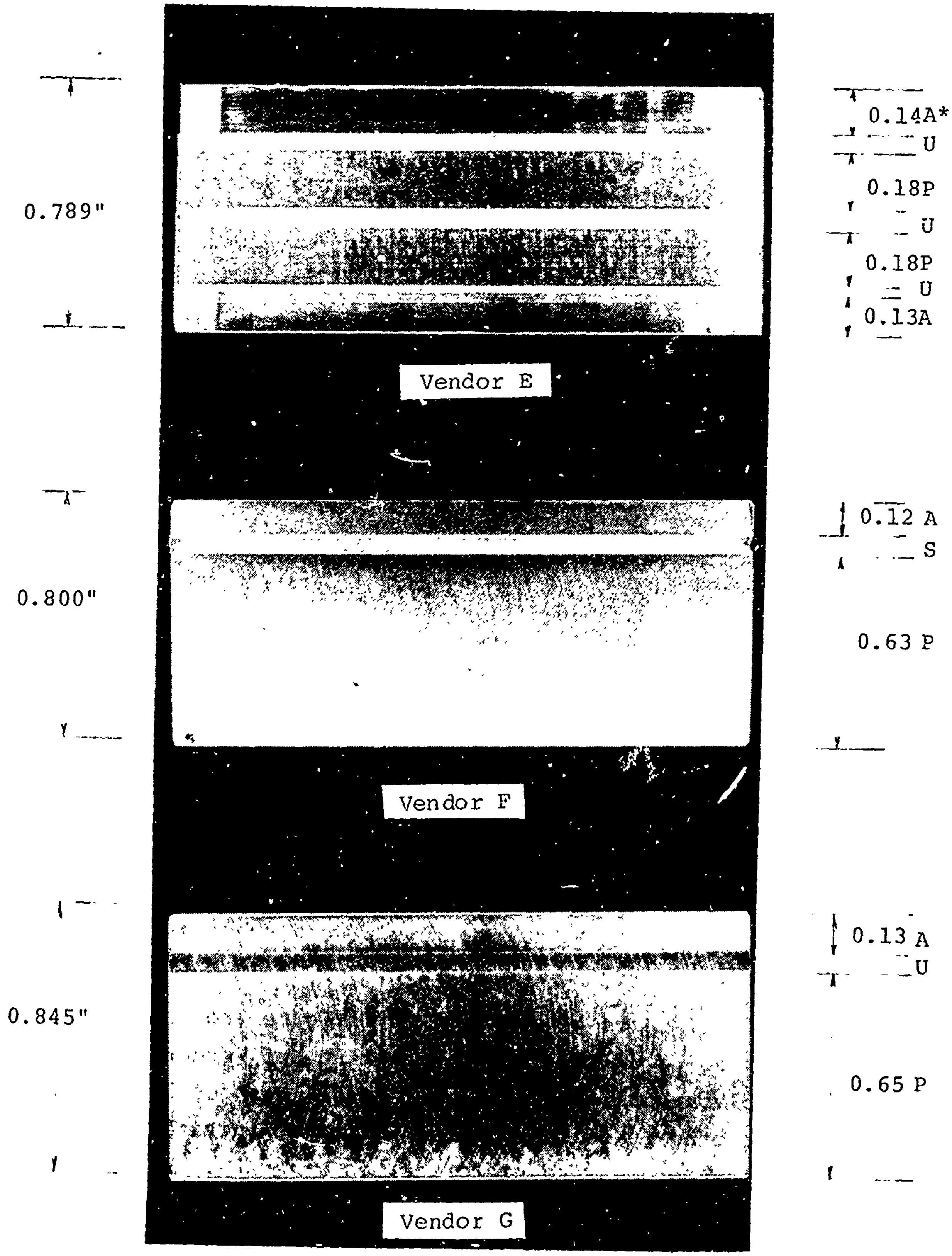
(vi) combined ultraviolet light with room temperature and high relative humidity (combined),

(vii) outdoor accelerated sunshine (EMMA-Equatorial Mount with Mirrors for Acceleration), and

(viii) EMMA plus water spray (EMMAQUA).

Accelerated laboratory conditioning was used to simulate the desired UV, moisture, thermal, and combined exposures. EMMA and EMMAQUA exposures were accomplished at the Desert Sunshine Exposure Test (DSET) Laboratory located in Arizona.

Eight types of tests were conducted; five being catagorized as structural-integrity/impact-resistance tests, namely falling weight impact, MTS beam flexure, air cannon, flatwise tension, and torsional shear. Two of these utilized beams of 1.50 inch width, 10.50 inch overall length and 0.75 inch depth, undergoing simply supported three point loading, specifically:



Specimen Cross Sections

Figure 1. Laminated Test Material.

*A denotes Acrylic
U denotes Urethane
P denotes Polycarbonate
S denotes Silicone

(i) an instrumented beam flexure test (MTS test) where the beam span was 6 inches and the displacement rate was a constant 2,000 in/min, maximum displacement was 2.50 inches with zero initial velocity, and

(ii) a falling weight impact test where the beam span was 4.50 inches to determine the threshold failure energy, that combination of falling weight times drop height, required to initiate a visible open crack in the beam specimen.

Air cannon tests were conducted using 12 inch x 12 inch plate specimens. Flatwise tension tests utilized 2 inch x 2 inch specimens and torsional shear tests were conducted using 5 inch x 5 inch plate specimens incorporating a 2 inch diameter x 2.25 inch diameter test ring.

In addition, three laboratory material tests were scheduled to determine the resistance of coated surfaces to specific environmental conditions. Rain erosion test specimens were mounted to an AFML rotating arm apparatus at a 30 degree incidence angle, then rotated through a stationary rain field. Chemical craze specimens were tested based on MIL-P-83310A and FTM 406, Method 6053, for the three chemicals: isopropyl alcohol, ethylene glycol, and MEK. Rubbing erosion tests were performed on a Bayer Abrader apparatus utilizing a layer of silica sand placed over the upper surface of a test specimen which is mounted with this surface flush to a movable test bed pan. The test bed and specimen is then oscillated back and forth while the silica sand remains virtually motionless, creating a rubbing type abrasion on the specimen upper surface.

A matrix of tests required to investigate the effects of environmental aging on the impact resistance of Vendor P coated monolithic polycarbonate, coated with C-254-1C on one side and GR-212 on the other side and representative of initial production F-16 canopy heat processing histories, is presented as Table 1. Additional developmental specimens as required were fabricated, conditioned, and tested using trial and error test runs to determine the approximate threshold of failure. Table 2

TABLE 1

PRODUCTION F-16 MONOLITHIC POLYCARBONATE TEST MATRIX[1]

Exposure Condition	Number of Tests		
	Falling Weight	MTS Beam	Air Cannon
Laboratory Simulation:			
Baseline			
GR-212 in tension	10	5	5
C-254-1C in tension	10	5	5
Uncoated	7	5	2
UV Radiation			
1-yr	5	5	5
2-yr	5	5	
3-yr	5	5	
5-yr	5	5	
10-yr	5	5	
UV/Humidity			
1-yr	5	5	
2-yr	5	5	
3-yr	5	5	
5-yr	5	5	
10-yr	5	5	
Moisture			
95% R.H., 2 wks.	5	5	
95% R.H., 6 wks.	5	5	
Thermal			
120°F, 6 wks.	5	5	
200°F, 2 wks.	5	5	
120°/250°F Spike	5	5	
Temp./Humidity			
120°F, 95% R.H.	7	7	
Lab Aged Control			
GR-212 in tension	5	5	
C-254-1C in tension	5	5	
Natural Accelerated:			
DSET Laboratories			
EMMA			
1-yr	5	5	5
2-yr	5	5	
3-yr	5	5	
5-yr	7	5	
EMMAQUA			
1-yr	5	5	5
2-yr	5	5	
3-yr	5	5	
5-yr	7	5	

Test	Condition	Number of Tests
Chemical Craze	3 solvents 4 exposures 2 replicates	24
Abrasion	4 exposures 5 replicates	20
Rain Erosion (500 mph)	Baseline 1-yr UV 3-yr UV	

[1]Note: All specimens coated with GR-212 inner surface and C-254-1C outer surface unless coded uncoated.

presents the test matrix for the specimens fabricated from coated monolithic polycarbonate sheet supplied by Vendor A and Vendor B. Table 3 presents the test matrix for the specimens fabricated from laminated polycarbonate sheet supplied by Vendors E, F, and G.

3. TEST SPECIMEN LAY-OUT AND IDENTIFICATION

The material used to fabricate the test specimens was received as large flat sheets. Specimen lay-outs were made onto the as-received sheets, and individual specimens cut according to these patterns. For Vendor A, which has the same coating on both faces, one face was arbitrarily chosen as the upper surface for all lay-out. For Vendor B, the same method was used. For Vendor P, since a different coating is used on each face, the GR-212 side was chosen (arbitrarily) as upper for lay-out. Figures 2 through 7 show the specimen lay-outs used for all monolithic and laminated sheets. As noted in Paragraph 1 of Section II, an acrylic ply protected the outer surface of Vendor E, F, and G laminates. For all specimens except rain erosion, the geometric shapes are rectangular prisms with the depth (thickness) remaining as-received. Each geometric shape was assigned an identification code letter, excluding the original 345 production beams used to generate the data base for comparison. Table 4 lists these codes, the nominal specimen dimensions, tests, and references. Fabrication details and critical dimensions are given in Paragraph 4 of Section II. The ID code was scribed onto each specimen; being a unique identifier for each specimen, consisting of a leading letter, a second letter, and a final two digit number. The leading letter identifies the vendor, either P, A, B, E, F, or G. The second letter identifies the geometric shape, either U (torsional shear), V, (flatwise tension), W (Bayer Abrader), X (rain erosion), Y (chemical craze), or Z (MTS and falling weight). The two digit number further identifies the specimen, and is related to its conditioning and testing. Since Vendor P uses a different coating on each

TABLE 2

VENDOR A/VENDOR B COATED MONOLITHIC POLYCARBONATE TEST MATRIX

Test	Exposure Condition	Number of Specimens
Falling Weight	2-yr. UV (14) Temp./Humidity (14) Combined (14) Baseline (14)	56
MTS Beam	2-yr. UV (10) Temp./Humidity (10) Combined (10) Baseline (10)	40
Chemical Craze	3 solvents 4 exposures 2 vendors 2 replicates	48
Rain Erosion (500 mph)	Unexposed Baseline 1-yr UV 3-yr UV	60
Abrasion	4 exposures 2 vendors 5 replicates	40
	Total	244

TABLE 3

LAMINATED POLYCARBONATE TEST MATRIX

Test	Exposure Condition	Number of Specimens
MTS Beam	3-yr. UV (15) Temp./Humidity (15) 200°F, 2 wks. (15) Baseline (15)	60
Flatwise Tension	3-yr. UV (15) Temp./Humidity (15) 200°F, 2 wks. (15) Baseline (15)	60
Torsional Shear	3-yr. UV (15) Temp./Humidity (15) 200°F, 2 wks. (15) Baseline (15)	60
	Total	180

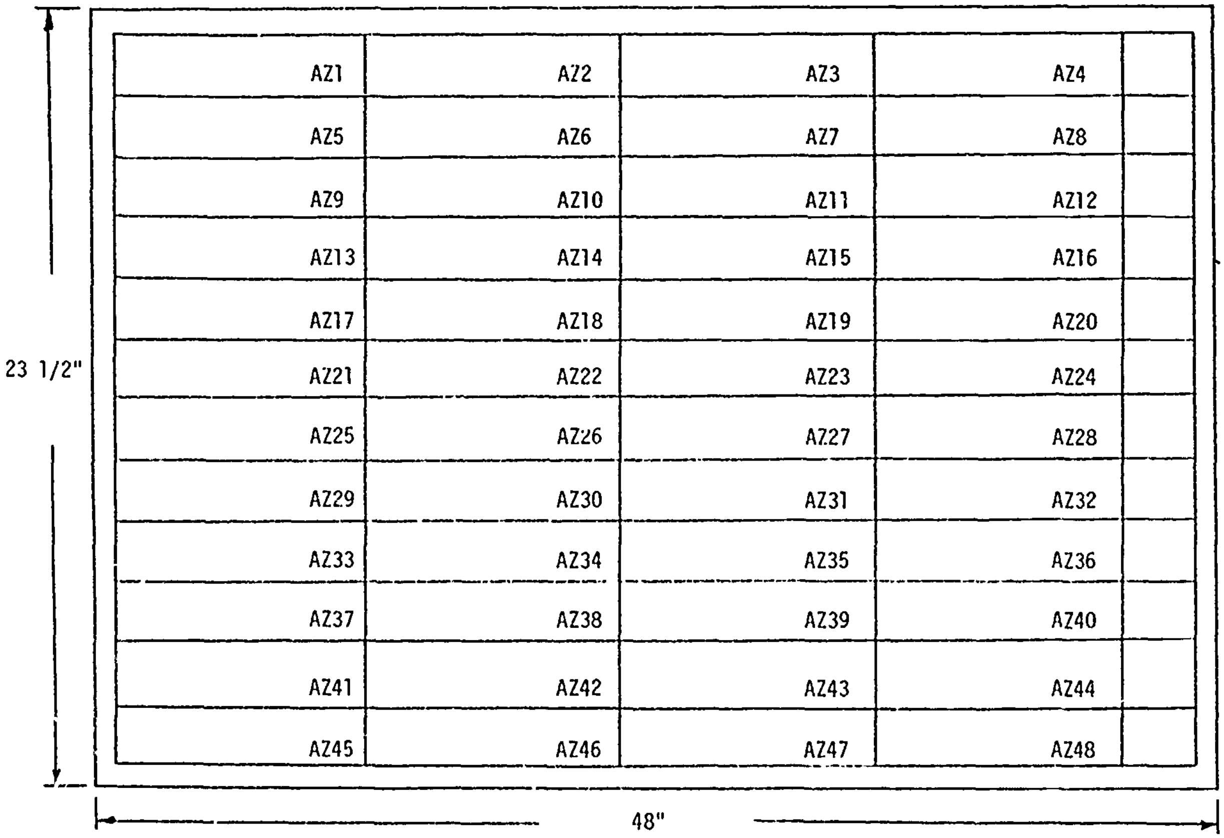
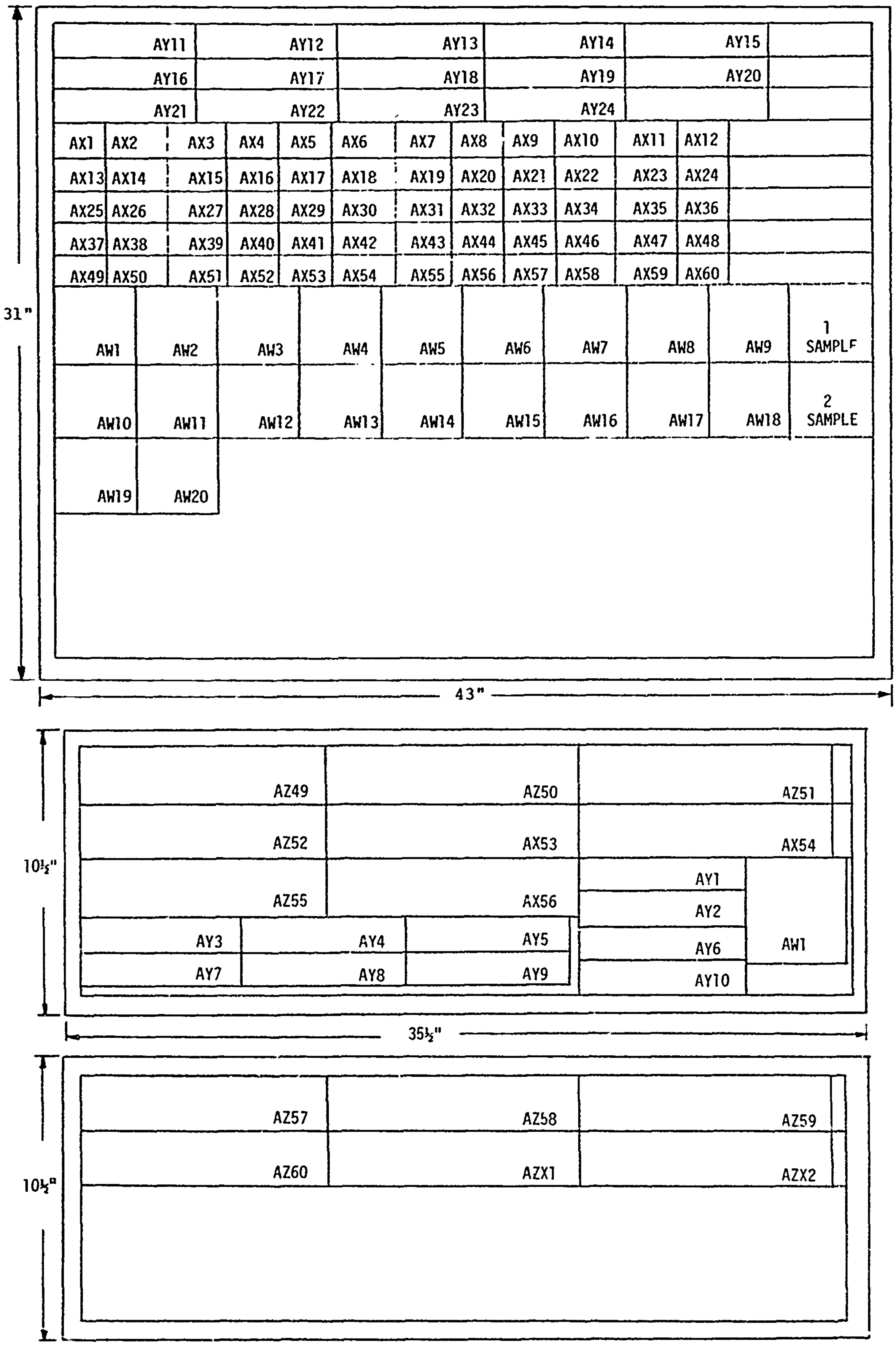


Figure 2. Specimen Layout - Vendor "A" Coated Monolithic Polycarbonate.



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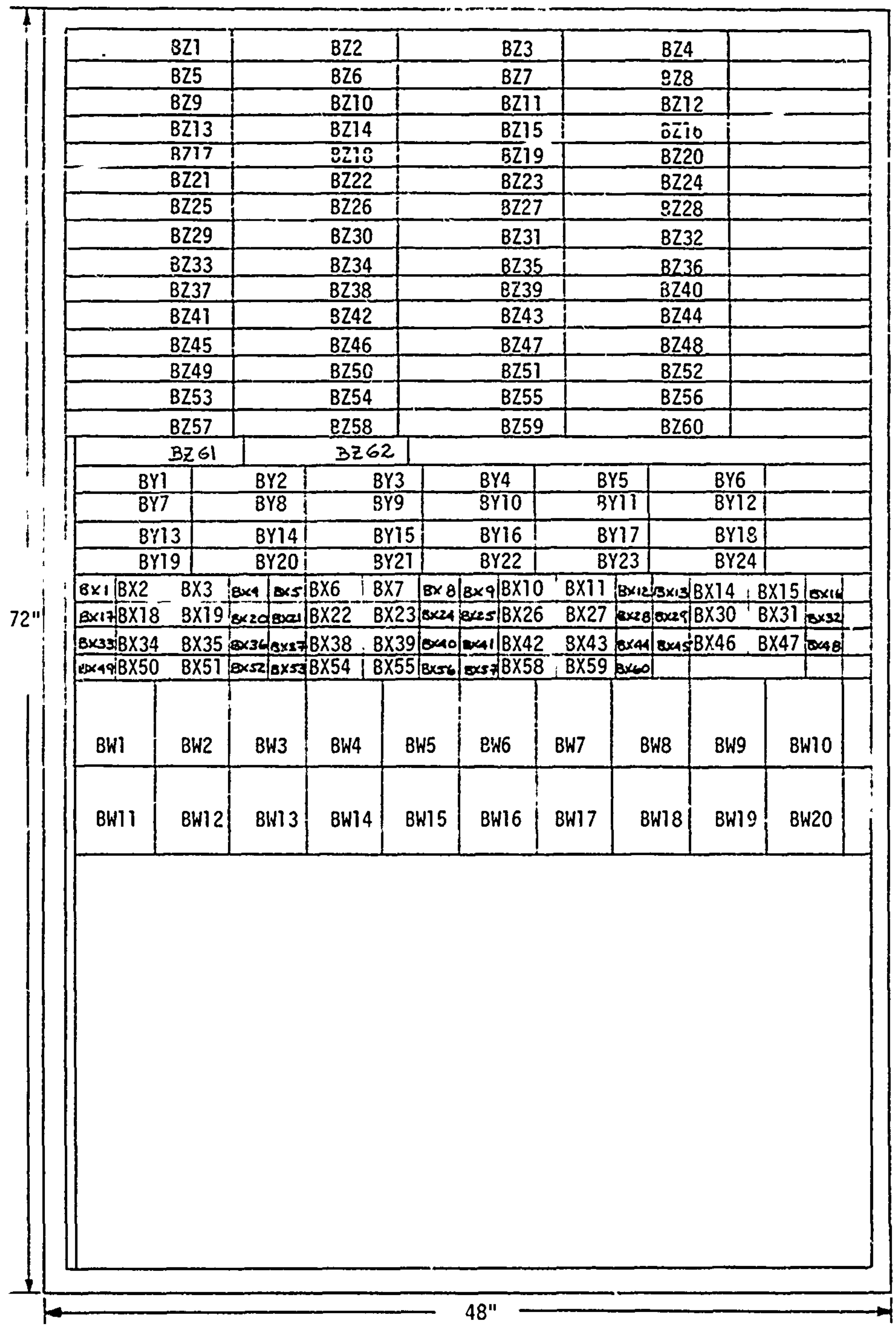


Figure 3. Specimen Layout - Vendor "B" Coated Monolithic Polycarbonate.

56"

1	24	47	70	93
2	25	48	71	94
3	26	49	72	95
4	27	50	73	96
5	28	51	74	97
6	29	52	75	98
7	30	53	76	99
8	31	54	77	100
9	32	55	78	101
10	33	55	79	102
11	34	57	80	103
12	35	58	81	104
13	36	59	82	105
14	37	60	83	106
15	38	61	84	107
16	39	62	85	108
17	40	63	86	109
18	41	64	87	110
19	42	65	88	111
20	43	66	89	112
21	44	67	90	113
22	45	68	91	114
23	46	69	92	115

43"

Sheet #001

Figure 4. Specimen Layout - Vendor "P" Coated Monolithic Polycarbonate.

56"

116	139	162	185	208
117	140	163	186	209
118	141	164	187	210
119	142	165	188	211
120	143	166	189	212
121	144	167	190	213
122	145	168	191	214
123	146	169	192	215
124	147	170	193	216
125	148	171	194	217
126	149	172	195	218
127	150	173	196	219
128	151	174	197	220
129	152	175	198	221
130	153	176	199	222
131	154	177	200	223
132	155	178	201	224
133	156	179	202	225
134	157	180	203	226
135	158	181	204	227
136	159	182	205	228
137	160	183	206	229
138	161	184	207	230

43"

Sheet #004

Figure 4. (continued)

56"

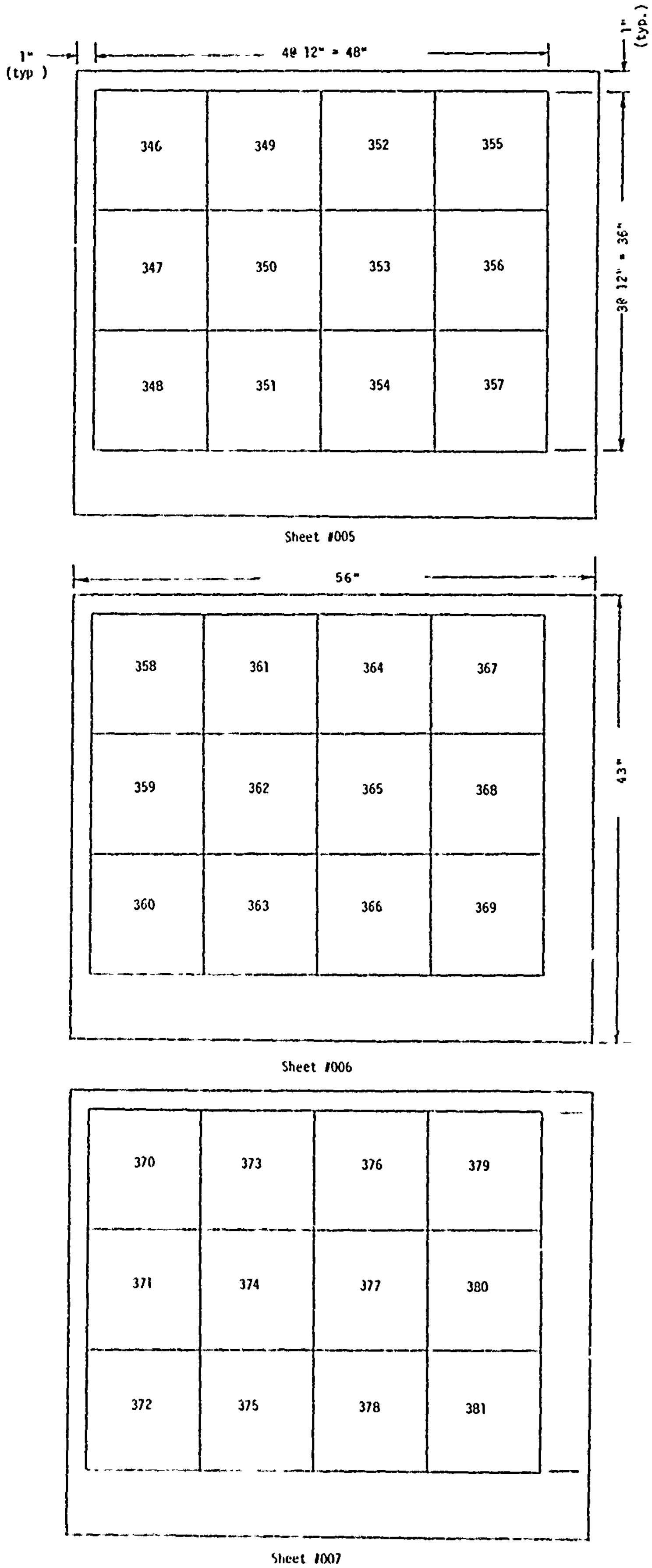
231	254	277	300	323
232	255	278	301	324
233	256	279	302	325
234	257	280	303	326
235	258	281	304	327
236	259	282	305	328
237	260	283	306	329
238	261	284	307	330
239	262	285	308	331
240	263	286	309	332
241	264	287	310	333
242	265	288	311	334
243	266	289	312	335
244	267	290	313	336
245	268	291	314	337
246	269	292	315	338
247	270	293	316	339
248	271	294	317	340
249	272	295	318	341
250	273	296	319	342
251	274	297	320	343
252	275	298	321	344
253	276	299	322	345

43"

Sheet #002

NOTE: Based on random numbers, falling weight impact/MTS beam specimens #1 through #345 were catagorized into 25 groups for environmental conditioning.

Figure 4. (continued)



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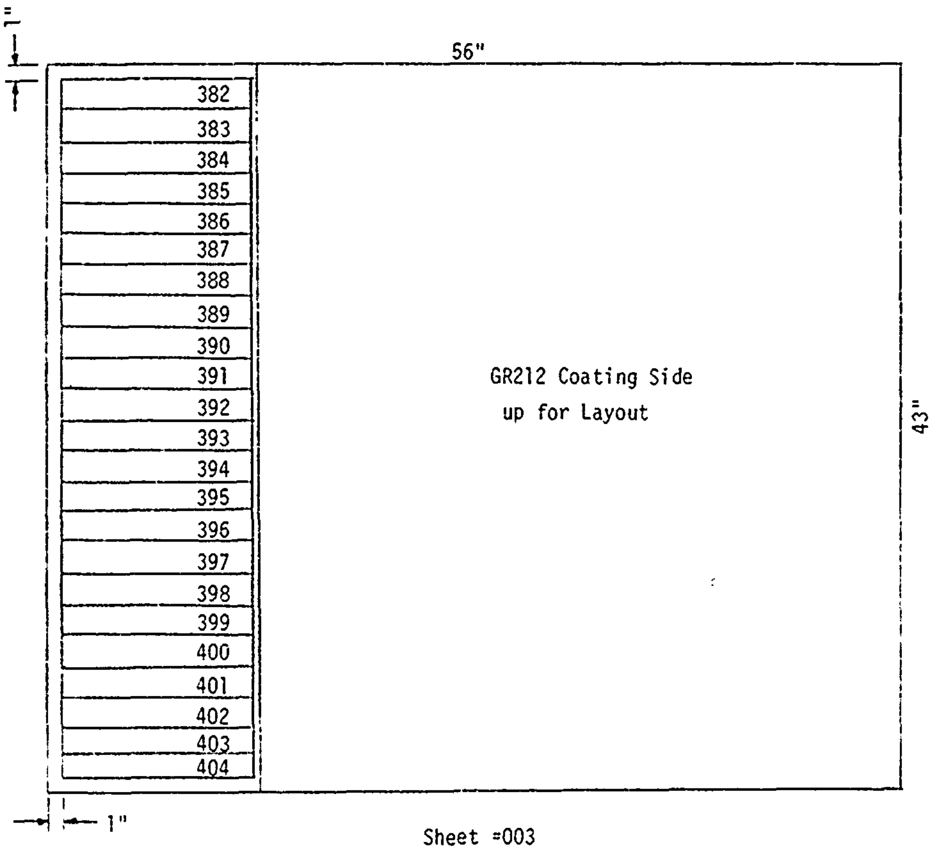

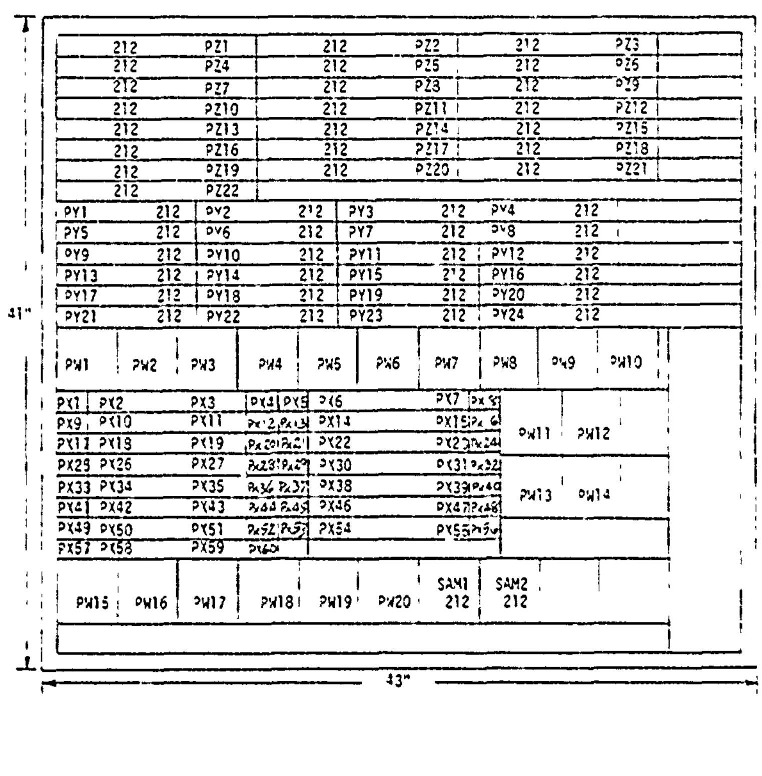

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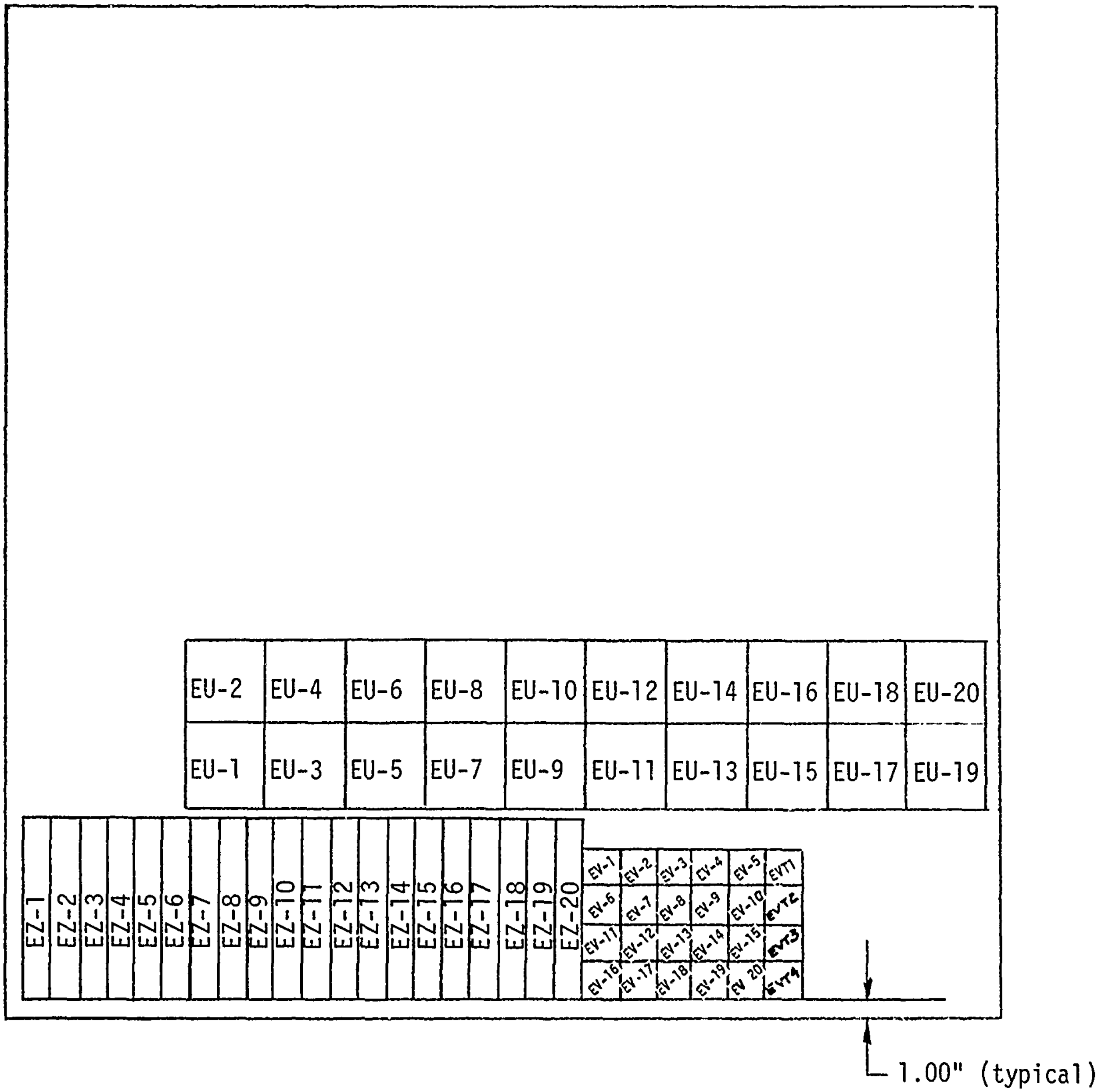


Figure 5. Specimen Layout - Vendor "E" Laminated Polycarbonate.

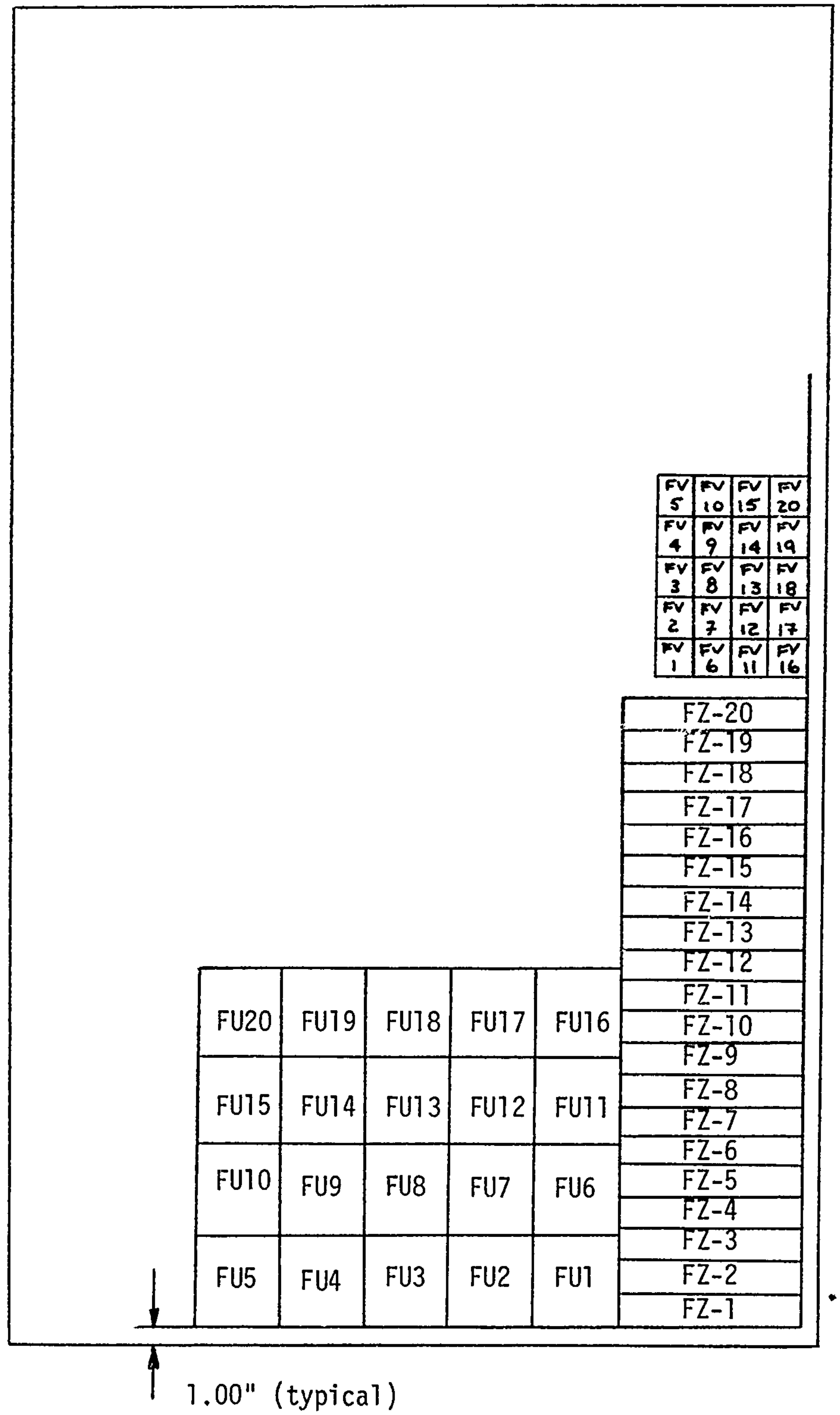


Figure 6. Specimen Layout - Vendor "F" Laminated Polycarbonate.

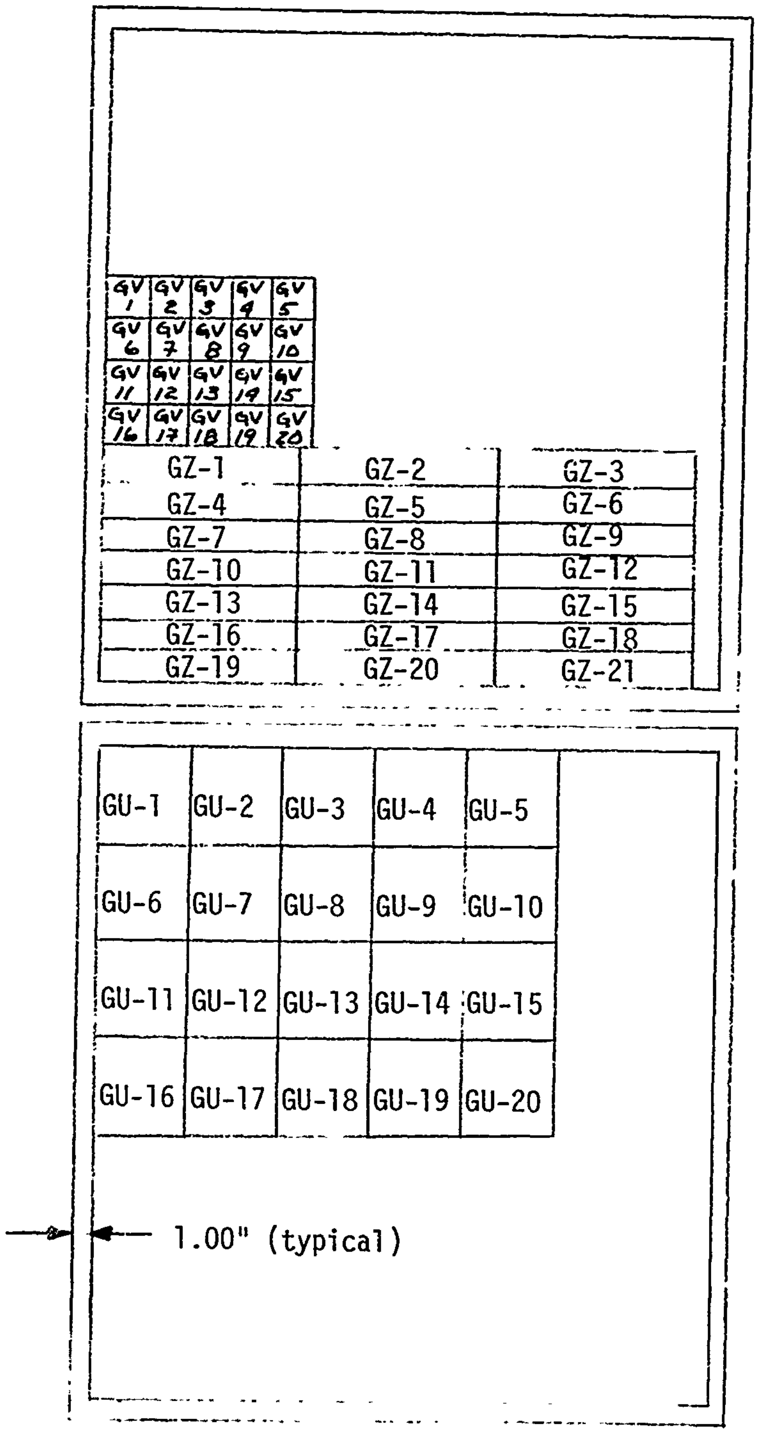


Figure 7. Specimen Layout - Vendor "G" Laminated Polycarbonate.

TABLE 4

TEST SPECIMEN GEOMETRY

ID Letter	Nominal Dimensions (inches)	Associated Tests	Reference Standards
Z	10.5L x 1.5W x 0.75D	MTS; Falling Weight	UDR-TR-80-06; Proposed ASTM Test Method
Y	7.0L x 1.0W x 0.75D	Chemical Craze	MIL-P-83310A; FTM406, Method 6053
X	Diagonal Ends, See Figure 8	Rain Erosion	AFML-TR-73-136, 30° Impact Angle
W	4.0L x 4.0W x 0.75D	Bayer Abrader	Proposed ASTM Test Method
U	5.0L x 5.0W x t	Torsional Shear	ASTM Test Method E229
V	2.0L x 2.0W x t	Flatwise Tension	ASTM Test Method D952

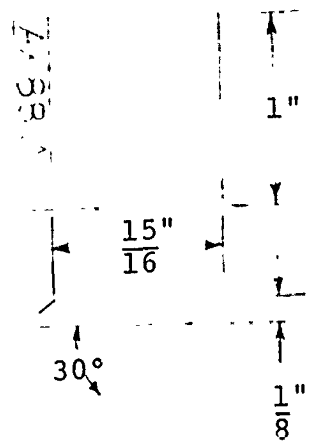


Figure 8. Rain Erosion Specimen, x Geometry.

face, it was also necessary to identify which coating was used on each face for Vendor P specimens. A complete listing of each specimen ID code and associated test parameters is included in Paragraph 7 of Section II.

4. TEST SPECIMEN FABRICATION

All specimen fabrication was accomplished in the UDRI machine shop. Polishing of the back face of rain erosion specimens was performed in the Metallography Laboratory. Sealing of exposed specimen edges with General Electric RTV 630 silicone was performed in the Plastics, Adhesives, and Composites Laboratory on all beam and laminated specimens prior to environmental conditioning.

All specimens were first cut from the parent material sheet by band-sawing. As necessary, selected sides of specimens (beam edges) were milled. Cutting temperature was controlled during milling through the use of cooling air. Polarized light inspection was used in conjunction with the milling operation to ensure that the level of residual machining stress was very low near the milled edges. Great care was taken to ensure that the coated surfaces to be tested were not damaged or adversely affected by fabrication.

The Z-geometry three-point beam specimens, used for MTS and falling weight impact testing, had the long sides (i.e., 10.5 inch dimension) machined dry in a vertical mill using a six flute 1 7/16 inch diameter cutter at 750 rpm and a table feed of five inch/minute, with both ends (i.e., 1.5 inch dimension) remaining as sawed. Additionally, the corners of the specimen edges were deburred using #400 emery paper in the region of critical loading. The achieved goal during testing was to initiate failure from the central surface, and not the edges, of the critical region of the specimen. Iterations between fabrication and test were used to develop milling and chamfer techniques to prevent edge initiated structural failures. The width tolerance for beam specimens was 1.500 $\pm$ 0.010 inches.

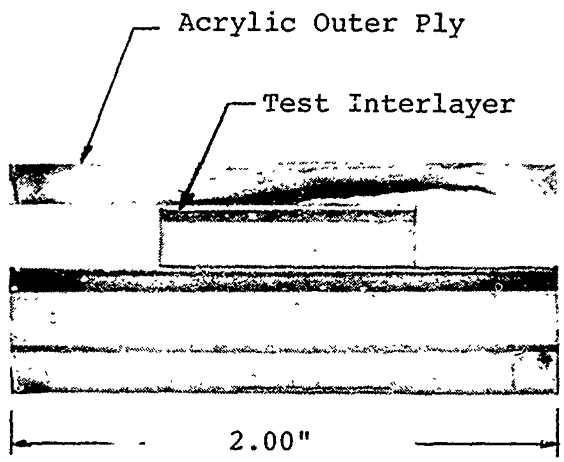
The fabrication of Y-geometry bars, used for chemical craze testing, was similar to that of the Z-geometry bars, except without deburred edges.

The X-geometry specimens, used for rain erosion testing, required a reduction in thickness and two beveled edges which were generated by milling. The test surface of the specimen, that coated surface to be exposed to rain erosion, was always protected during milling. This was done either by keeping the protective paper used by the vendor on the test surface during milling, or by seating the test surface on a teflon spacer bar or layer of teflon tape during milling. After milling, the back face of each rain erosion specimen was polished to a level which allowed meaningful visual, haze, and transmittance inspection during rain erosion testing. Care was taken to keep from damaging the test surface during the polishing of the back face.

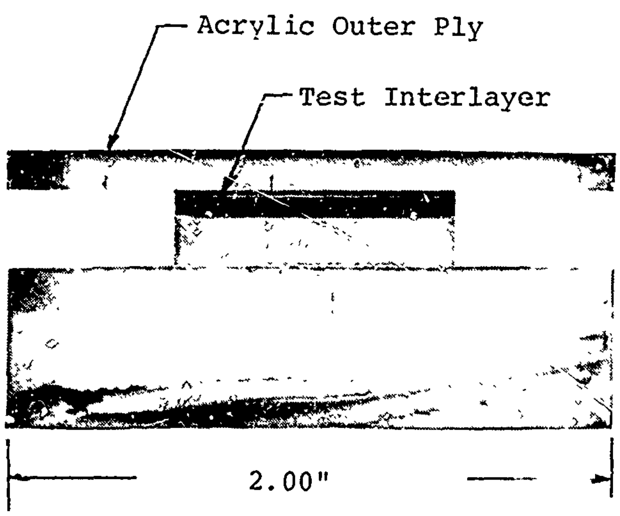
The W-geometry specimens, used for Bayer Abrader testing, were milled on all four sides.

The V-geometry specimens, used for flatwise tension testing of laminated material, were machined with an end mill to the required 2x2-inch ($\pm$.010) size. Specimens cut from Vendor E and G material were slotted with a 1/4 inch diameter end mill to a 1x1-inch size in the area of the interlayer after exposure. (Reference: Figure 9.)

The U-geometry specimens, used for torsional shear testing of laminated material, were bandsawed to the required 5x5-inch size. After environmental conditioning, a 3/4" hole was drilled in the center of each specimen for mounting purposes. The outer and inner annular grooves were machined in the specimen from opposite sides to form the test ring having an inner diameter of two inches and an outer diameter of 2 1/4 inches as shown in Figure 10. The outer groove was machined first to avoid any unnecessary stress in the test ring. The tolerances on this specimen were $\pm$.010" on the test ring width and $\pm$.010"



VENDOR E



VENDOR G

Figure 9. Modified Flatwise Tension Specimens.

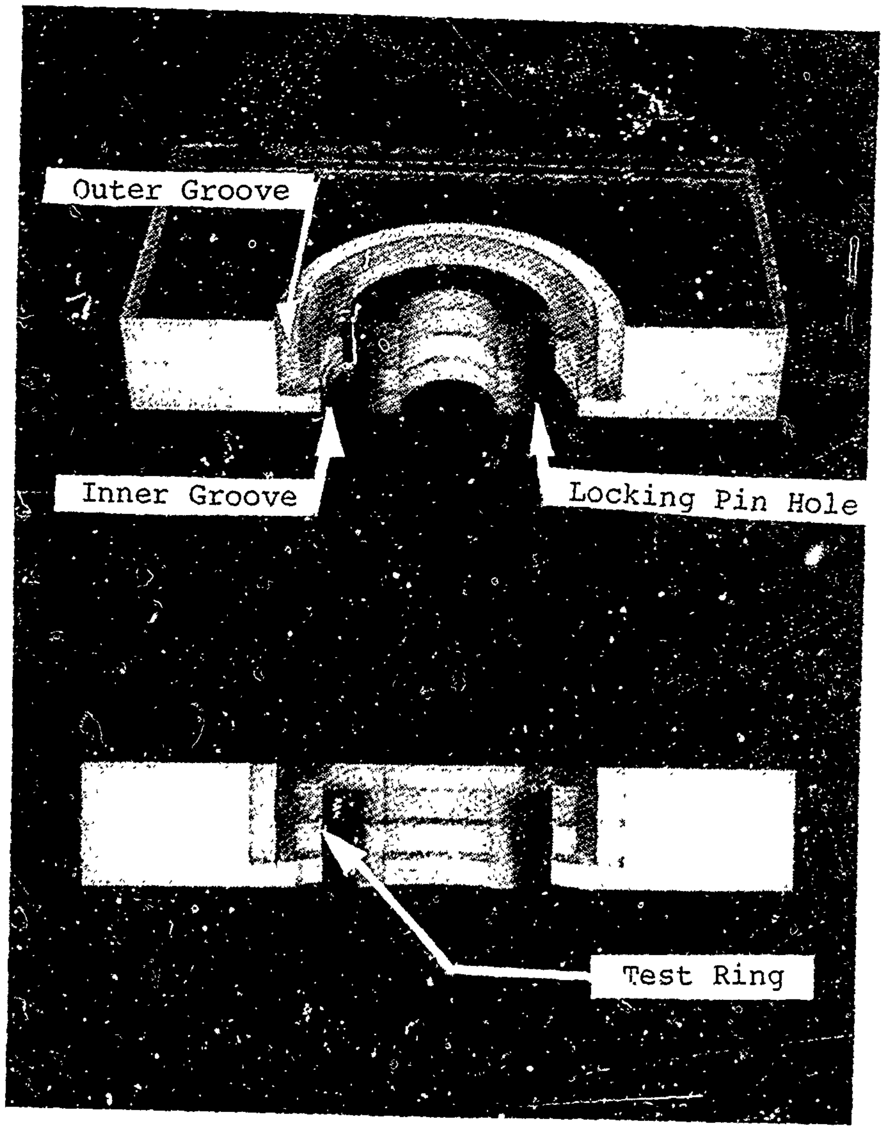


Figure 10. Sectioned Torsional Shear Specimen.

on concentricity. A number 20 hole was drilled in the inner portion of each specimen to accommodate a locking pin used to prevent rotation of the specimen relative to the load cell.

Plate specimens for air cannon testing were bandsawed to 12 x 12-inch; no finish machining being required.

Identification codes were scribed on each specimen after machining. Beam specimens were individually poly-bagged for protection prior to distribution.

5. ENVIRONMENTAL CONDITIONING

Environmental conditioning was implemented in three ways: as received baseline consisting of no exposure, accelerated laboratory conditioning at UDRI, and accelerated outdoor sunshine exposure at the Desert Sunshine Exposure Test (DSET) Laboratory in Arizona.

Accelerated laboratory conditioning:

The ultraviolet (UV), temperature and humidity, and combined exposures were all accelerated laboratory exposures.

All ultraviolet conditioning was performed using a "Sunlighter IV" accelerated sunlight tester, manufactured by the Test-Lab Apparatus Company, Amherst, New Hampshire as shown in Figure 11. Basically, this apparatus consists of four sunlamp bulbs mounted over a rotating turntable. The tester acceleration ratio over natural sunlight is based on a cabinet temperature of 130°F-140°F. The energy level in the range where nearly all UV degradation occurs, supplied by the General Electric RS-4 sunlamp bulbs in the tester, varies from a wavelength of 290 millimicrons (nanometers) at an intensity of 1300 watts/sq. meter to 360 millimicrons at 30,000 watts/sq. meter, peaking at 314 millimicrons at approximately 150 000 watts/sq. meter; the wavelength of maximum sensitivity for polycarbonates being 295 millimicrons. Specimens were mounted on a screen to avoid contact with the non-reflective turntable.

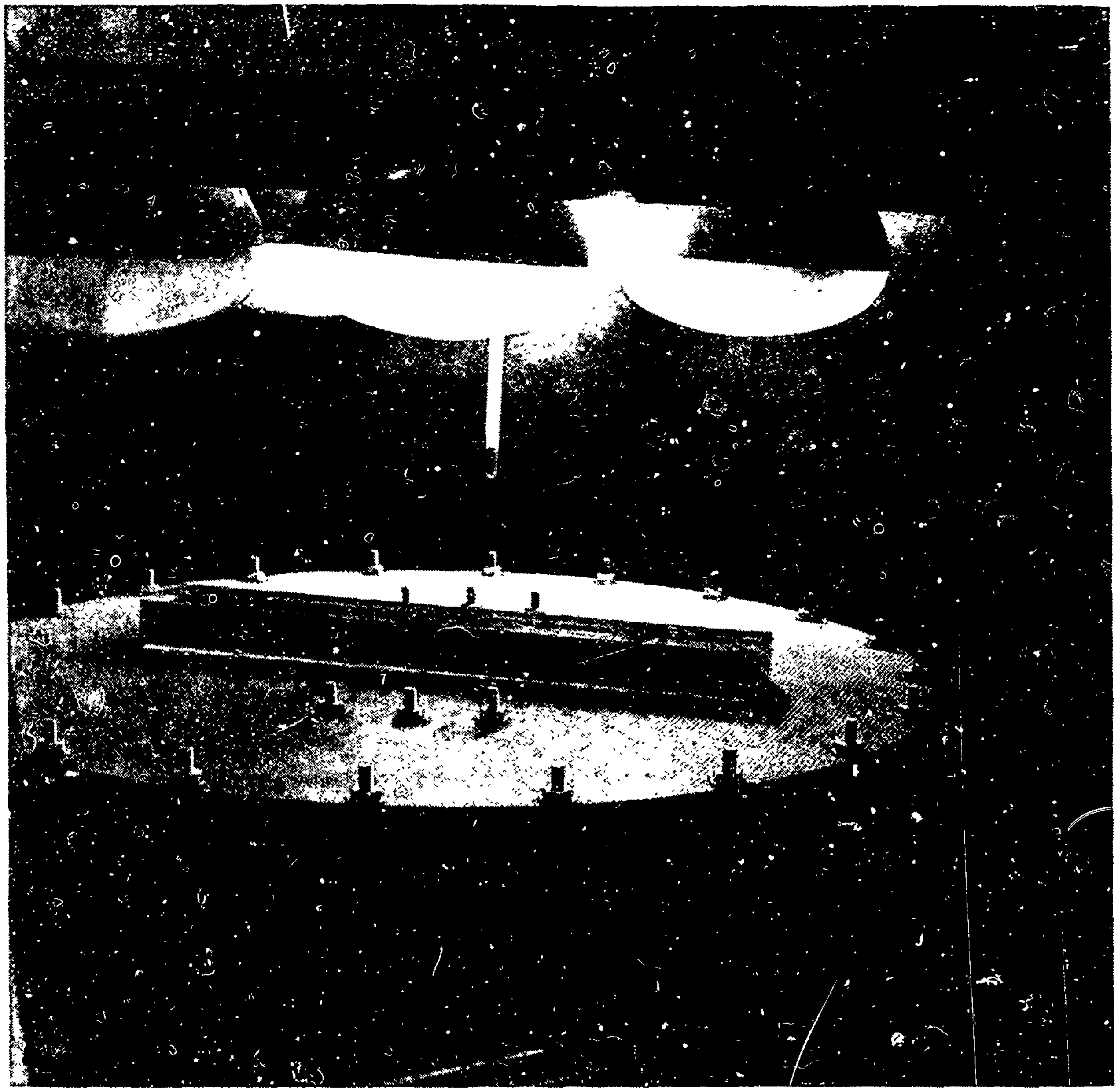


Figure 11. Accelerated UV Exposure in "Sunlighter IV" Apparatus.

The tester components, associated power, and control electronics are mounted in a box enclosure with a tinted plexiglas viewing door. One sunlamp bulb is mounted directly over the center portion of the turntable, and three additional bulbs are mounted over the outboard portion of the turntable. Consequently, two areas with different exposure accelerations are produced on the turntable, an inner circle of approximately six inch diameter, and the remaining outer ring to 17.5 inch diameter. For the inner circle, the acceleration ratio is approximately eight hours exposure: one year natural sunlight. For the outer ring, the acceleration ratio is 56 hours exposure: one year natural sunlight, according to the manufacturer. The inner circle was used for all UV exposures to MTS, falling weight impact, chemical craze, flatwise tension, and rain erosion test specimens. UV exposure for all Bayer Abrader and torsional shear test specimens was performed on the outer ring of the Sunlighter IV.

Temperature and humidity conditioning was performed in three environmental conditioning chambers, each producing equivalent results. Each is capable of maintaining closely controlled temperature and relative humidity. The three chambers are a Humidaire, manufactured by Blue M Electric Company, Blue Island, Illinois, a Tenney Model No. 469917 and a Tenney Ten, both manufactured by Tenney Engineering, Union, New Jersey. Figure 12 shows the Tenney Model No. 469917, which is functionally equivalent to the other chambers. A temperature of 120°F with simultaneous 95 percent $\pm$ 5 percent relative humidity was the laboratory exposure used for all temperature/humidity conditioning. An acceleration ratio of 48 hours exposure: one year simulation was used.

The combined conditioning consisted of periods of UV exposure alternating with periods of room temperature/high humidity exposure. The procedure was identical to that used for individual exposure conditions. The following sequence was

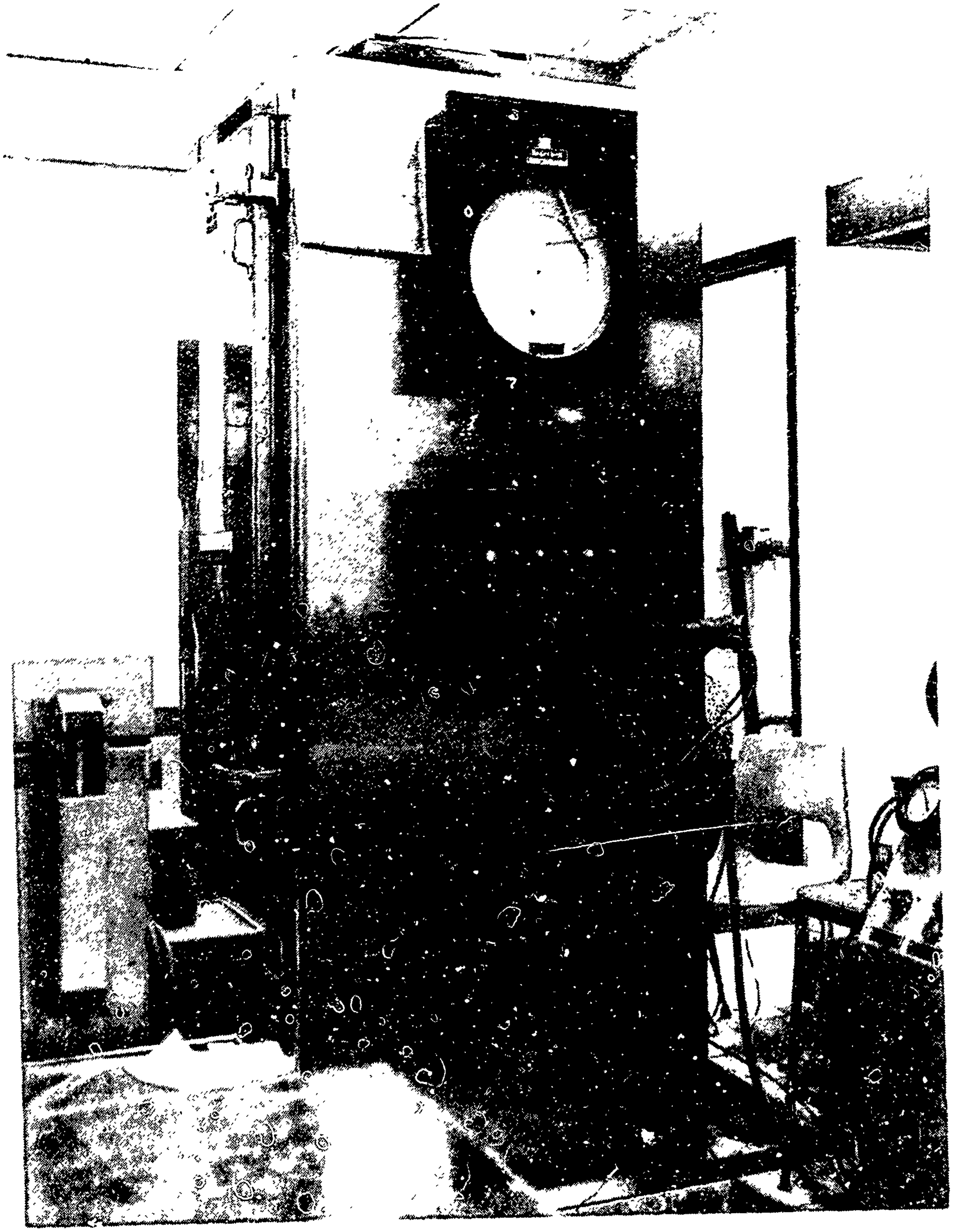


Figure 12. Temperature/Humidity Conditioning Chamber.

used to obtain each simulated year of exposure: a period of eight hours in the inner circle of the Sunlighter IV, followed by a period of 48 hours in the room temperature/95 percent relative humidity chamber.

Thermal exposure was obtained at steady-state temperature of 120°F, 200°F or 250°F as desired, in an air-circulating oven having a heating and cooling rate of 3-5°F/minute.

Accelerated outdoor sunshine conditioning:

Accelerated outdoor weathering of simulated one, two, three, and five year exposure was accomplished by utilizing the Equatorial Mount with Mirrors for Acceleration (EMMA) machine and the EMMAQUA machine (EMMA plus water: eight minutes per hour spray cycle) at the Desert Sunshine Exposure Test (DSET) Laboratory located at 25 miles north of Phoenix, Arizona. It is estimated that 40 days of exposure on the EMMA and/or EMMAQUA machine is approximately equivalent to one year of 45-degree south natural weathering. The specimens receive about eight times as much radiation as those exposed on a follow-the-sun rack during equal periods of time. Each simulated year was based on an exposure rate of 164,250 langleys.

6. TEST PROCEDURE

The following tests were conducted to evaluate the coated monolithic polycarbonate material: MTS beam, falling weight impact, air cannon, chemical craze, rain erosion, and Bayer abrasion. In addition to the MTS beam tests, flatwise tension and torsional shear tests were conducted to evaluate the laminated acrylic/polycarbonate material.

(a) MTS Beam Test

The MTS beam test is an instrumented flexure test utilizing three-point simply-supported loading. Figure 13 shows the equipment used to conduct these tests in the UDRI Structural Testing Laboratory. The MTS test machine is a high performance general purpose mechanical loading apparatus with high level

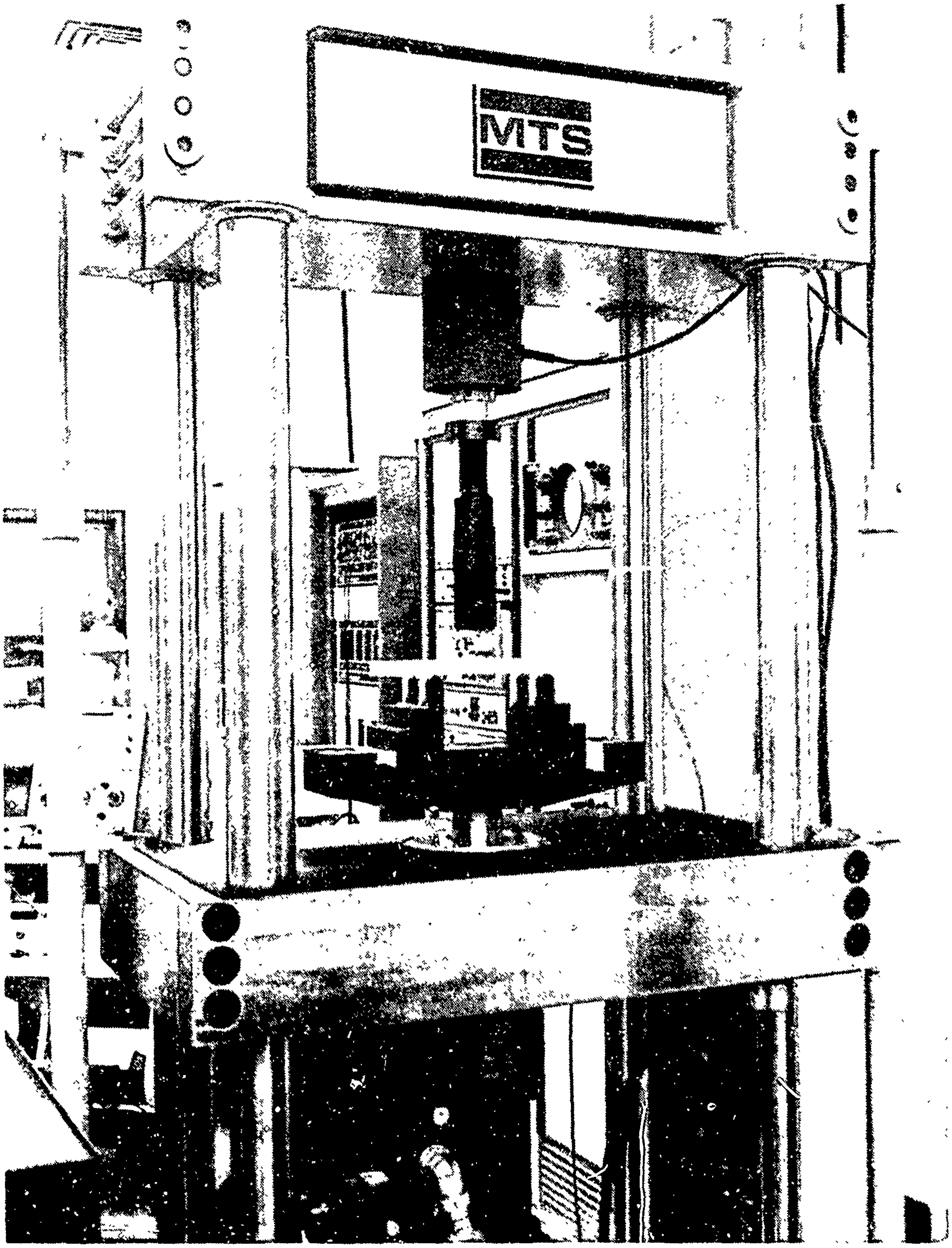


Figure 13. High Performance Electrohydraulic Closed Loop Test System.

control and data gathering capabilities. It consists of the following major components; a servohydraulic power pump, a specimen holding fixture, a reaction load frame, appropriate transducers, an electronic feedback controller operating the actuator through an electrically controlled hydraulic servovalve, and suitable data gathering, storage and recording instrumentation. It is a system of matched components manufactured by MTS Systems Corporation, Minneapolis, Minnesota. Appropriate specific components and parameters were utilized for the structural beam tests throughout this program. A mounting fixture was used to provide three-point simply-supported loading to the center of each specimen as shown in Figure 14; the contact radius of each loading support being 3/8 inch. The span between supports was 6.0 inches for the Z size (10.5 in x 1.5 in. x 0.75 in.) specimen providing an 8:1 span-to-depth ratio. The specimen was centered in the fixture with the test surface down, producing tension in the coated surface under investigation. The two outer supports are part of the loading yoke below the specimen. This yoke is positioned above the vertically mounted actuator, and is attached to the top of the ram: the yoke moving upward to load the specimen. Ram position was measured by an LVDT (Linear Variable Differential Transformer), with this signal being sent as the feedback signal to the analog electronic feedback controller for the actuator; the command signal for the controller being generated by a selectable function generator. Displacement rate was controlled to be 2,000 inches/minute. Peak displacement was set at 2.50 inches. The center loading support remained stationary during testing. The upper part of the center support was attached to the stationary load frame. Both load and displacement were set at zero when the specimen just touched the loading fixture. The calibrated output signals of both the LVDT and load cell were captured in a dual channel digital transient waveform recorder and then played back on an X-Y recorder to document load versus displacement for each MTS beam test specimen.

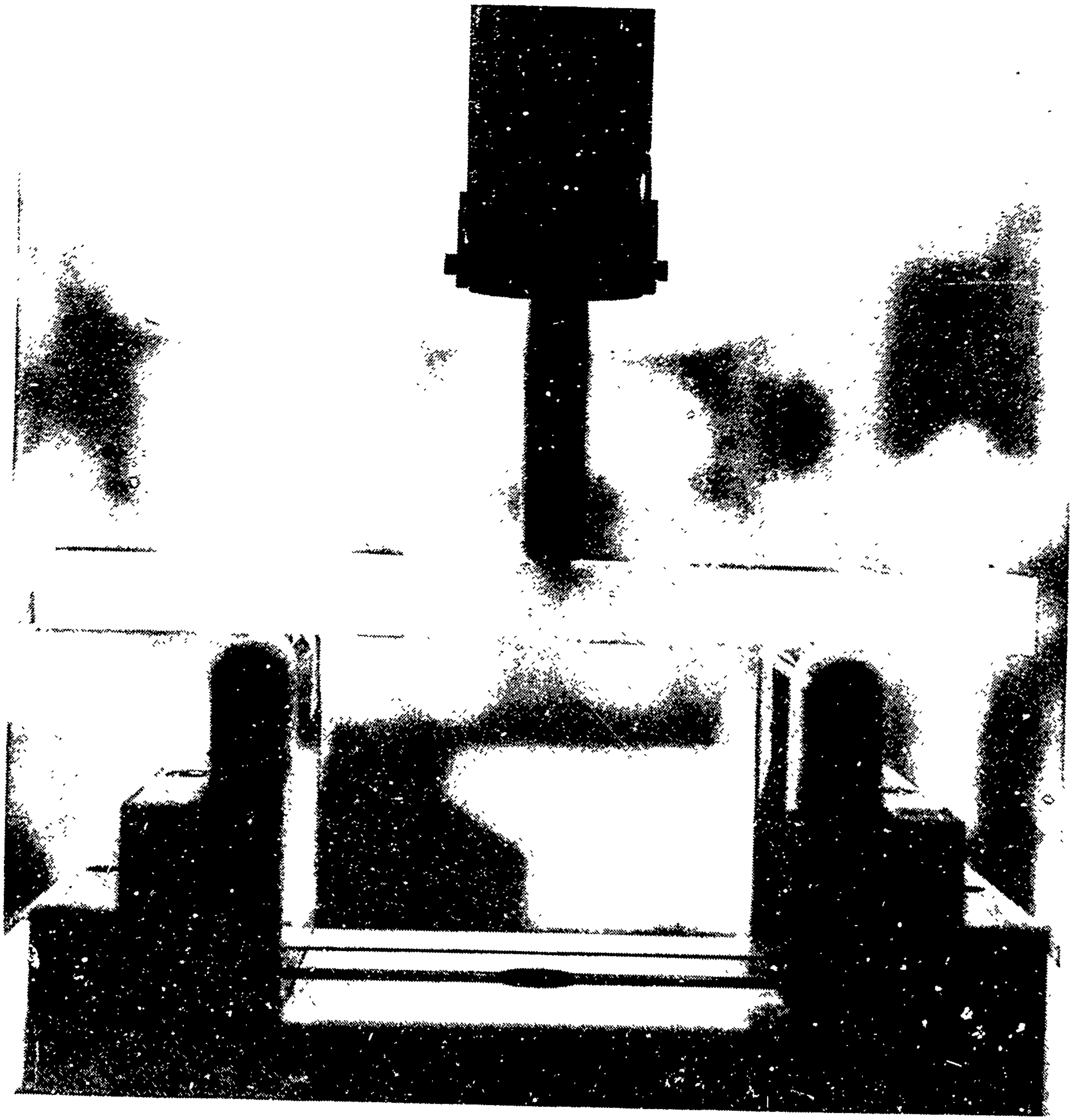
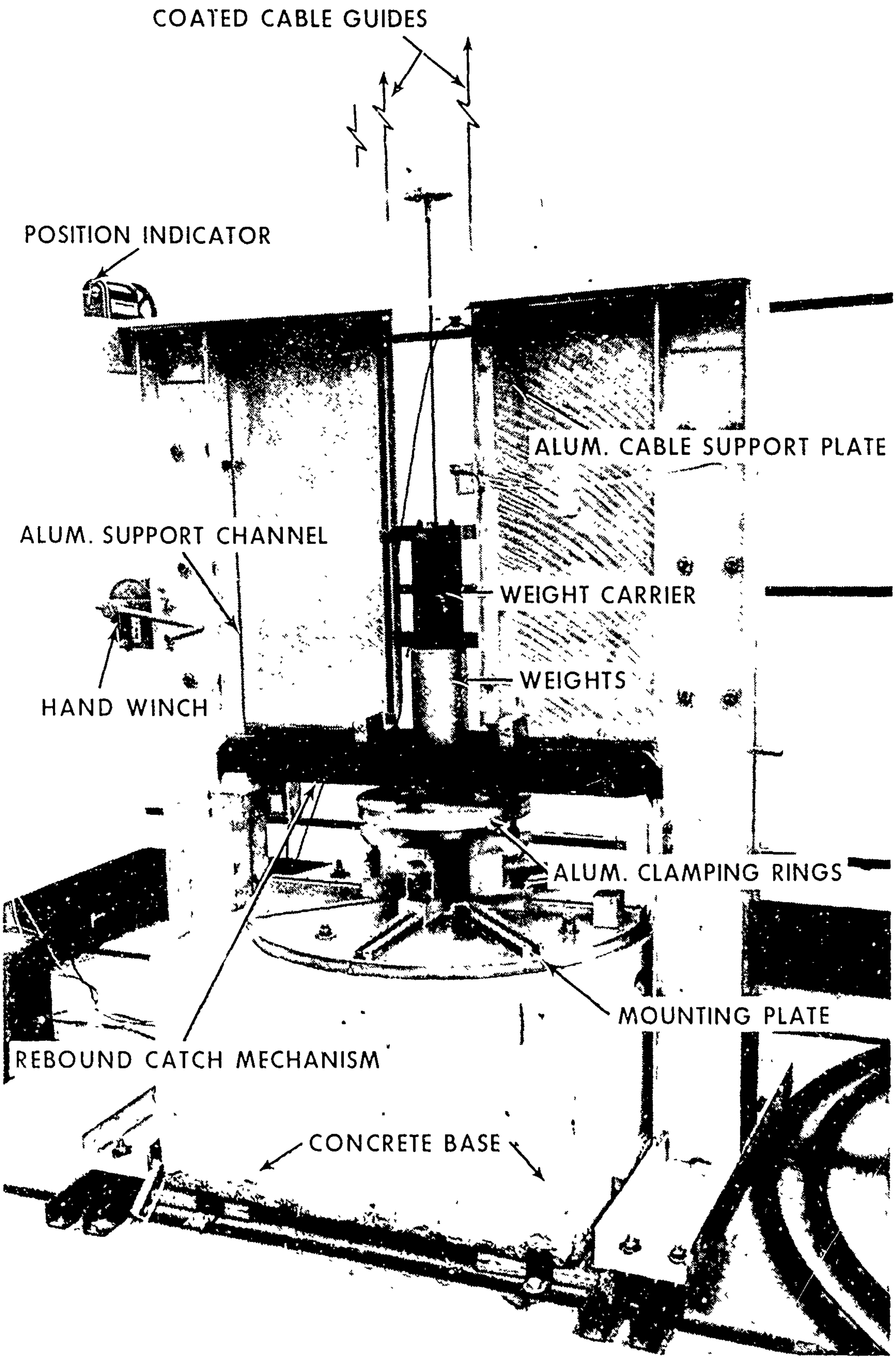


Figure 14. Test Set-up: Simply-Supported MTS Beam.

(b) Falling Weight Impact Test

The falling weight impact tests utilized three-point simply-supported flexural beam loading and falling weight velocities of approximately 25 to 34 ft/sec, corresponding to drop heights of 10 to 18 feet, respectively. The falling weight impact test apparatus, designed, fabricated and installed at the University of Dayton is shown in Figure 15. This tester will accommodate simply-supported or clamped plate specimens of various span/thickness ratios as well as simply supported beams of varying span/thickness ratios. A lifting carrier is provided to raise or lower the impactor to a maximum drop height of 20 feet, adjustable and measurable to the nearest half-inch. Drop weights are detachable, interchangeable, and variable in known increments from one pound to a total of 50 pounds. Hemispherical impactors of one-half-, one-, and two-inch diameter geometry are available and interchangeable for impact testing of plates. A 2.25-inch wide impactor loading nose and adjustable supports, corresponding to ASTM D790-Method I, are available for three-point impact testing of simply-supported beams. A two-cable system guides the falling weight so that it will repeatedly strike within 0.10-inch of center of the specimen at an impact velocity approaching free fall. Automatic release and rebound catch mechanisms are provided along with a protective enclosure used to contain any flying particles which may be generated during test.

Although no instrumentation was used to quantitatively evaluate the candidate coated monolithic polycarbonate falling weight beam specimens, a miniature accelerometer can be mounted in the impactor housing to obtain a load-time history when desired. The signal from the accelerometer is triggered two inches before impact by a photocell, and received throughout the impact event. The accelerometer signal is integrated twice to obtain velocity and displacement, a scaling factor being used to obtain force. An X-Y recorder is utilized to play back, at reduced speed, the test data which had been stored in the memory of a transient recorder. Z-geometry specimens, 10.5 in. x 1.5 in.



[illegible] Weight Test Apparatus.

x 0.75 in., identical to the MTS beams, were used for the falling weight impact tests, except that the span was 4.5 inches (6:1 span-to-depth ratio). The two beam supports are attached to the stationary mounting plate. The specimen was centered on top of these supports with its coated test surface (tension side) down. The center load was the impactor nose of the falling weight as shown in Figure 16. The goal of this testing was to produce threshold of failure in the specimen using the following procedure; threshold of failure being defined as a visible open crack. The weight of the falling weight assembly was measured and recorded. The impactor nose was initially rested against the test specimen to set zero height. The falling weight assembly was raised manually by the fixture's cable and winch to a predetermined height. The solenoid was triggered to release the falling weight, which, in turn, transferred its potential energy into kinetic energy during free fall; the impactor nose impacting the specimen at a velocity determined by its initial height. A rebound catch mechanism ensured that the falling weight impacted the specimen only once. The mass and height were iterated during testing to determine the energy level required to achieve threshold of failure.

(c) Air Cannon Test

Twenty-five air cannon tests were conducted using 12 x 12-inch square plate specimens fabricated from the same lot of 3/4 inch thick monolithic polycarbonate material, incorporating C-254-Cl outside coating and GR-212 inside coating. The UDRI ballistic range was set up to use a one-inch diameter steel sphere projectile launched in a polycarbonate sabot by a 1 1/2 inch bore, six foot long gun. Each plate was taped with double-sided tape to a picture frame support, providing free-edge mounting. Instrumentation was provided to measure impact velocity.

(d) Chemical Craze Test

Chemical craze tests were conducted to determine the resistance of the polycarbonate surface coating to chemical crazing. This testing was based on MIL-P-83310A, Paragraph 6.d(2) of Section IV, and FTM 406, Method 6053 using the test fixture shown in Figure 17. The test fixture loaded the specimen as a class I

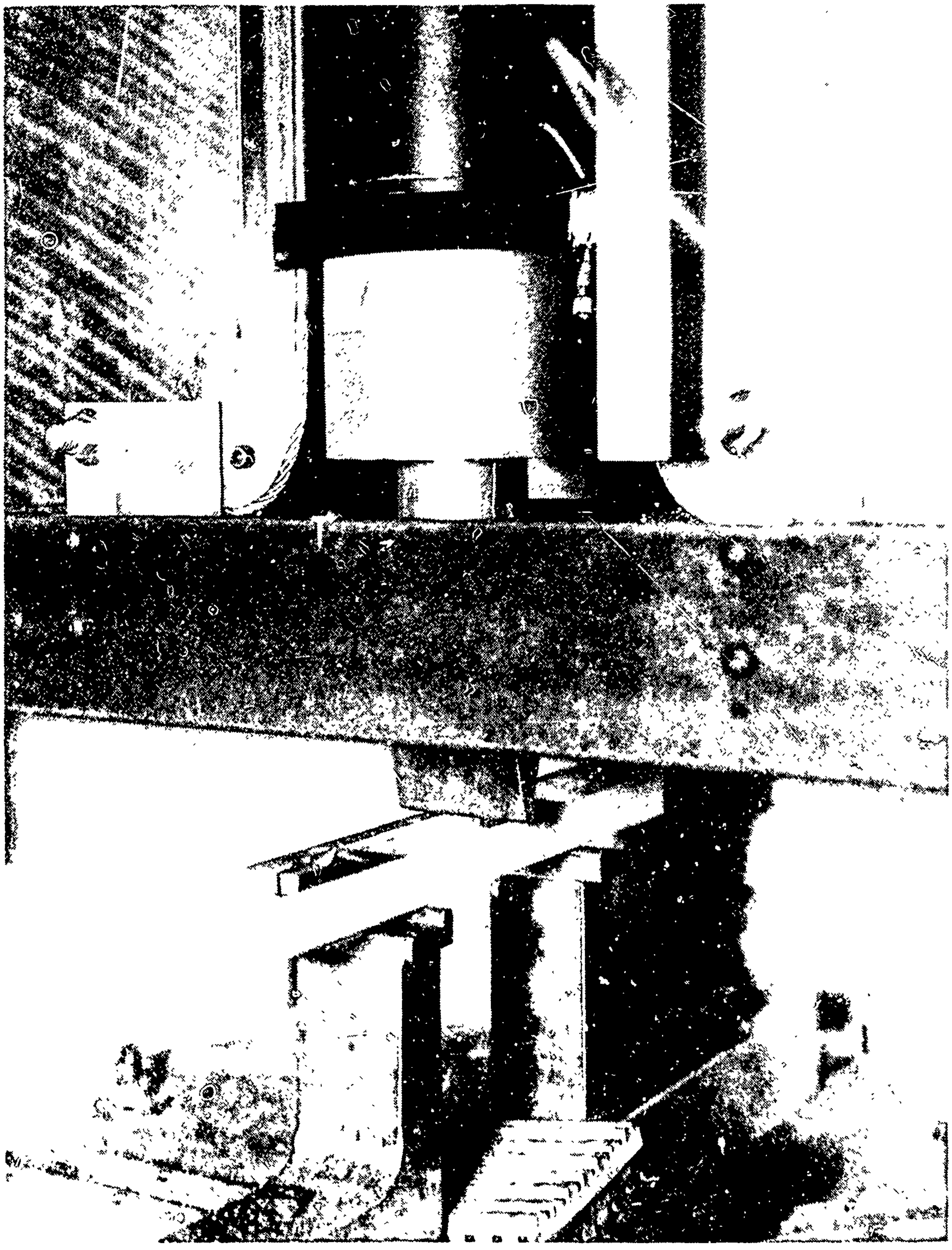


Figure 16. Test Set-Up: Falling Weight Tester.

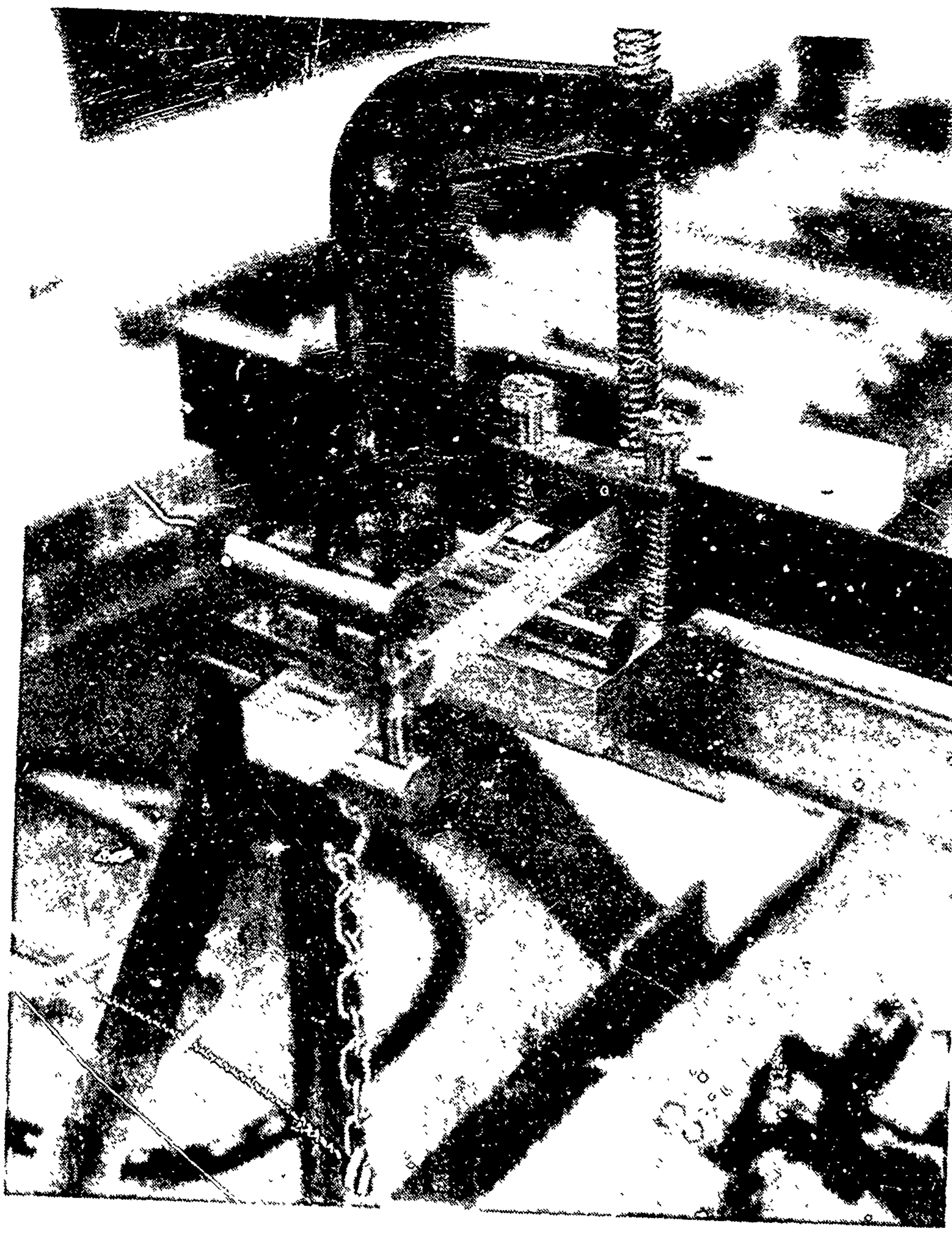


Figure 17. Chemical Craze Test Fixture.

lever, with the (fixed) fulcrum 1.5 inches from the (fixed) reaction point, and the applied weight overhanging the fulcrum by 4.0 inches as shown in Figure 18. The Y-geometry beam specimens (7.0 in. x 1.0 in. x 0.75 in.) were inserted into the fixture with the critical coated surface opposite the fulcrum. An applied load of 48 lbs. was applied to produce a nominal 2000 psi outer fiber tensile stress in the critical region of the coated upper surface directly above the fulcrum. The specimen was gradually loaded to 48 lbs., then allowed to stabilize for 10 minutes. Each of three solvents, isopropyl alcohol, ethylene glycol, or MEK (Methyl Ethyl Ketone) was applied to the critical region of the specimen by placing a 0.5 inch square filter paper patch soaked in the solvent onto the upper surface of the specimen, centered directly above the fulcrum. The patch remained on the specimen for 30 minutes (if catastropic failure did not occur sooner). The patch was removed and the surface under the patch visually examined for damage.

(e) Rain Erosion Test

Rain erosion tests were conducted using the AFWAL Materials Laboratory's rotating arm apparatus at a speed of 500 mph with the specimens inclined at 30° to the direction of motion.

(f) Bayer Abrader Test

The Bayer Abrader test, recently developed by A. G. Bayer, West Germany, was used to evaluate rubbing erosion. Test specimens (4 x 4 inches square) were positioned in a 4 x 4-inch cavity of the test bed so that the specimen surface was flush with the bottom of the test bed. One kilogram of 6/14 quartz silica sand was placed over the specimen. A mechanical linkage to an electric motor moved the test bed in a back and forth motion and 4-inch stroke length at a frequency of 150 cycles per minute (300 strokes per minute). This action causes the silica sand to remain virtually at rest inducing a rubbing type abrasion on the specimen. These tests were conducted using the Bayer Abrader. Haze measurements were taken initially (unabraded) and after 50, 100, 150, and 300 strokes using a standard sphere Hunter Hazemeter and

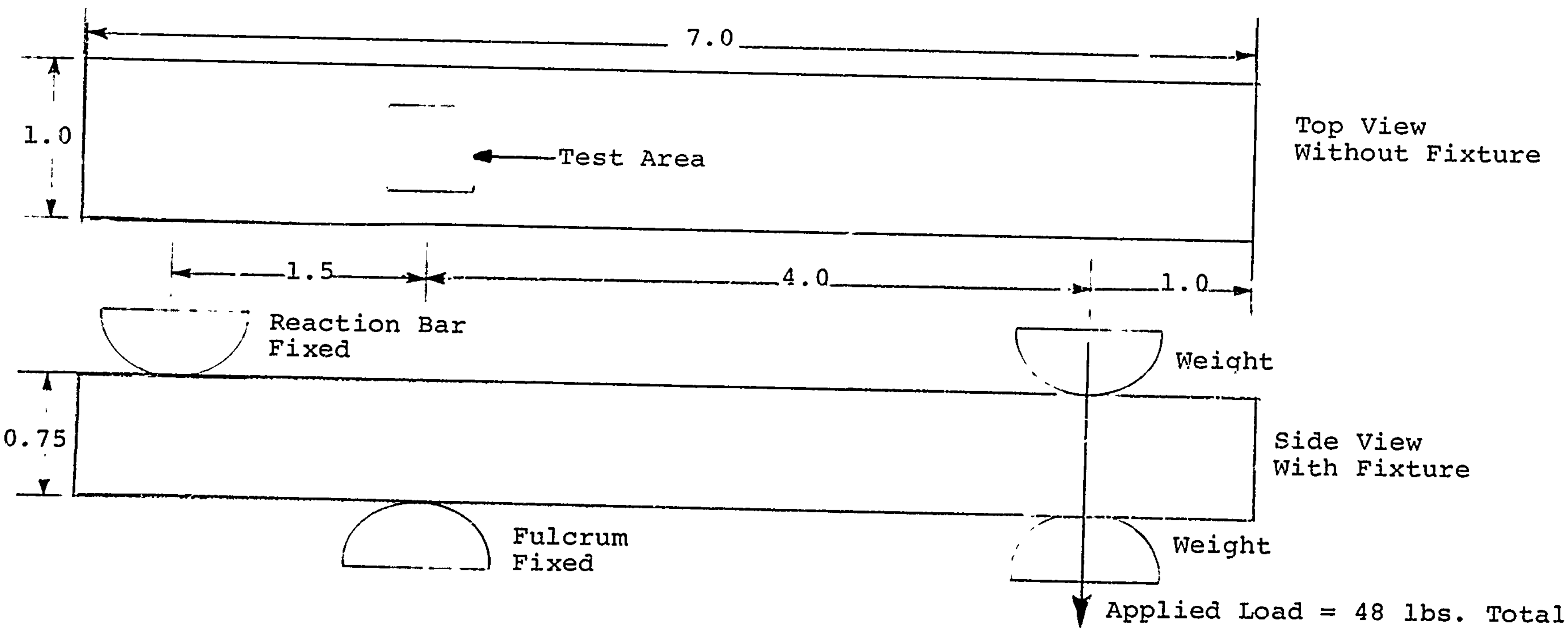


Figure 18. Test Set-up: Chemical Craze.

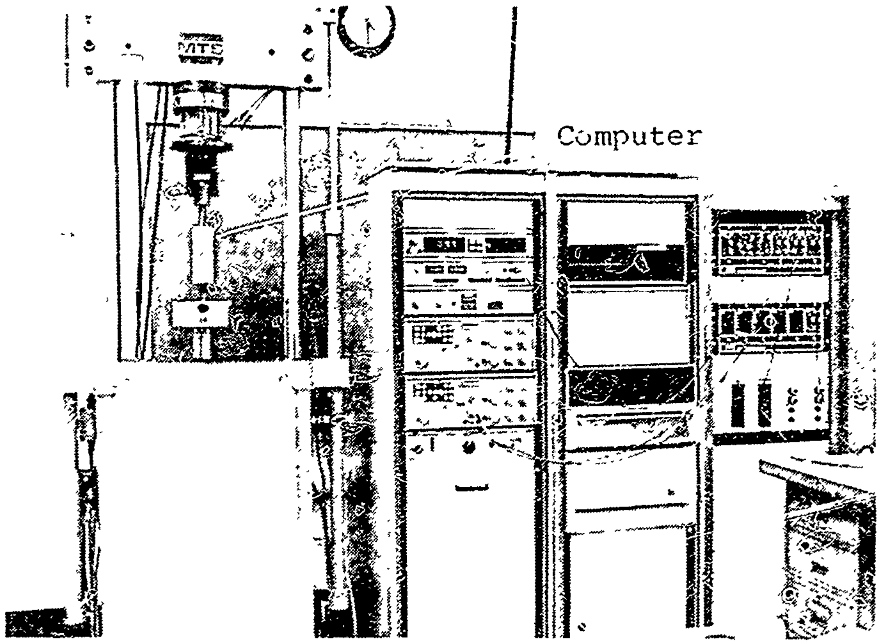
Gardner Photometric Unit manufactured by Gardner Laboratory, Inc., Bethesda, Maryland. The construction of the hazemeter used is described in ASTM Test Method D1003.

(g) Flatwise Tension Test

Flatwise Tension tests of laminated material were conducted in accordance with ASTM Test Method D 952. The test was designed to determine the flatwise tensile stress required to delaminate the material. The two-inch square specimens were bonded to two-inch square aluminum blocks using EA-9320 room curing adhesive. The bond strength averaged 1375 psi which was not sufficient to cause failure in Vendor E and G material. The two candidate materials which could not be failed directly were modified by cutting the cross-sectional test area down to one square inch instead of the original four square inches while maintaining the four square inches bond area. The modified specimens, previously shown in Figure 9, were tested using the same specified techniques. The specimen/aluminum block assembly was bolted in the high performance MTS test machine as shown in Figure 19. The specimens were loaded at a rate of 10,000 lb/sec for a displacement of two inches, and the peak force was recorded.

(h) Torsional Shear Test

Torsional shear tests of laminated material were conducted using ASTM Method E 229 as a guideline. This test was designed to determine the shear force required to delaminate the candidate material. Torque was applied to the outside of the specimen through a clamping fixture with the electrohydraulic MTS tension-torsion machine shown in Figure 20. The inside of the specimen was held fixed to the load cell with a locking pin and set screw assembly, after being torqued to 150 percent of the predicted failure torque. This design produced a peripherally uniform stress distribution through the test area without inducing bending, peeling or transverse shear. These were conducted at an angular velocity of 500°/sec., which produced a maximum shear rate in the test ring of 589 in/min. The fixed test angular displacement was 50°. The maximum stress in the interlayer at failure represented the shear strength of the interlayer.



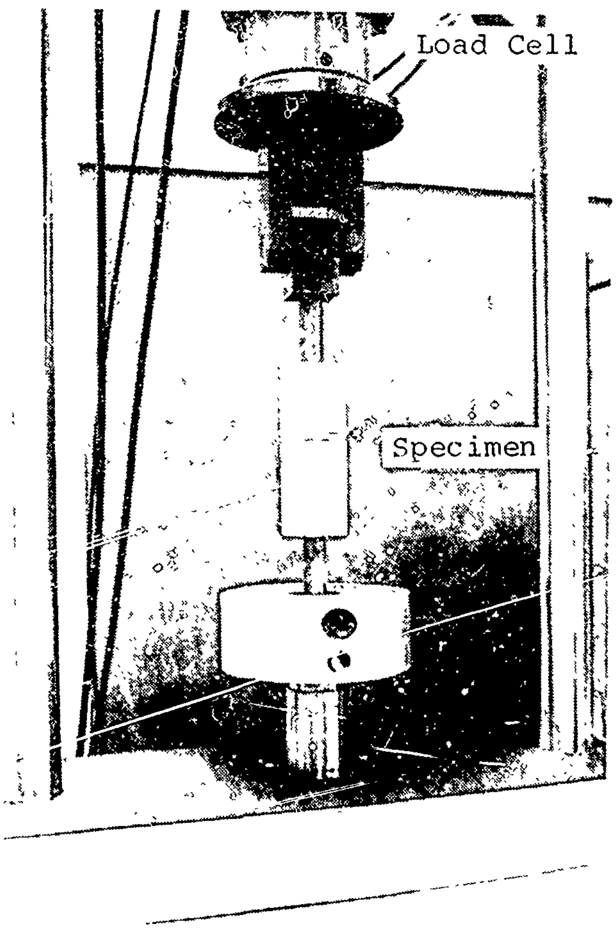


Figure 19. Test Set-up: Flatwise Tension.

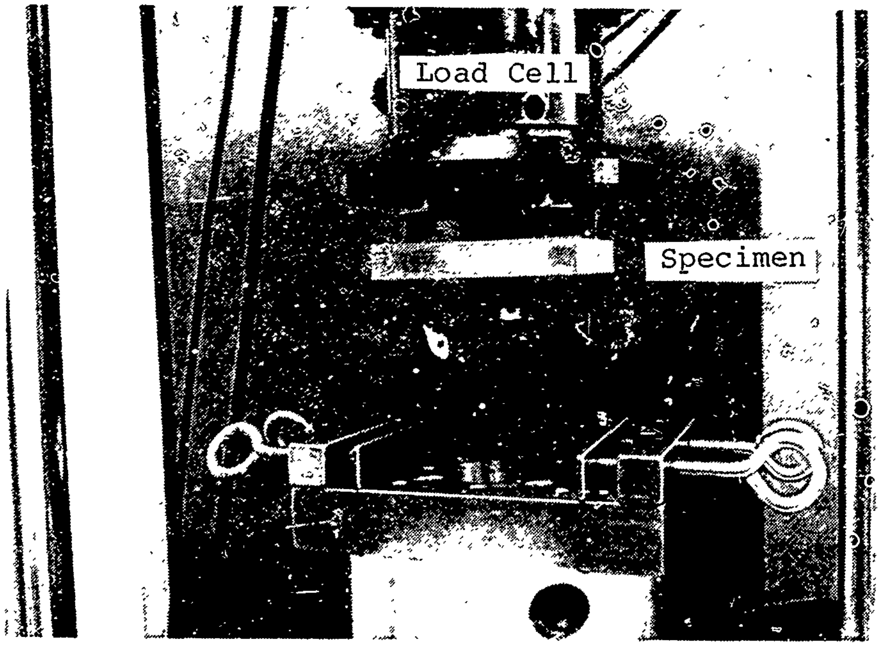


Figure 20. Torsional Shear Specimen Mounted in Test Machine.

7. TEST RESULTS

A total of 791 tests, excluding rain erosion, were conducted at UDRI to investigate the behavior and determine the change in behavior, if any, of monolithic and laminated polycarbonate sheet, representative of F-16 canopy material. The data generated by this test program is documented in the following paragraphs.

(a) Test Data - Coated Monolithic Polycarbonate

A total of 190 MTS flexural beam tests were conducted using an 8:1 span-to-depth ratio. Plots of load versus displacement were recorded for each test; typical curves being presented as Figures 21 through 24. The integral of force times displacement (area under the curve) was measured from the zero point to maximum load carrying displacement (2 1/2 inch cutoff). Resultant energy levels for all test conditions are presented in Table 5 for Vendor P, Table 6 for Vendor A, and Table 7 for Vendor B. In all cases, the surface under investigation was tested in tension. Unless otherwise noted, all MTS flexural beam tests were run at a loading rate of 2000 inches per minute.

A total of 260 falling weight impact tests were conducted using 6:1 span-to-depth ratio beams and an impactor nose and supports corresponding to ASTM Method D790-I. The most complete data base was generated for Vendor P coated monolithic polycarbonate; resultant energy levels (falling weight x drop height) for all test conditions being presented in Table 8. Vendor A data is presented in Table 9; Vendor B data in Table 10. The response of each specimen was catagorized into one of three failure response levels as follows: threshold of failure designated by the initiation of an open crack visible to the naked eye: ductile deformation occurring below the threshold of failure; and penetration or catastrophic failure above the threshold of failure accompanied by the beam specimen splitting in two parts. As with the MTS beams, the surface under investigation was tested in tension.

Twenty-five air cannon tests were conducted using plate specimens fabricated from Vendor P material. In addition, two shots were made using plate specimens cut from 3/4 inch thick uncoated monolithic polycarbonate. Test results are presented in Table 11.

Seventy-five chemical craze tests were conducted using beam specimens fabricated from Vendor A, B, and P material with test results presented in Table 12.

Sixty abrasion specimens, 15 (5 replicates each) of Vendor A, B, and P material for four conditions, were tested using a Bayer Abrader. Percent haze was measured at 0, 50, 100, 150, and 300 strokes with data presented in Table 13.

Rain erosion test results are presented in Appendix A.

(b) Test Data - Laminated Polycarbonate

A total of 180 tests were conducted on the candidate laminated acrylic/polycarbonate canopy materials; the results being presented in Tables 14 through 16. Although the number of tests and conditions were limited, these tests did indicate trends and showed differences between each of the candidate materials. The following paragraphs discuss the test results.

Sixty MTS beam (three-point flexure) specimens were tested by deflecting the midpoint of the simply-supported beams 2 1/2 inches. The energy consumed in straining the specimens was recorded as a load vs. displacement curve. The average energy levels of five replicates for each test condition is summarized in Table 14. These levels indicate the energy absorbed by the specimen during the 2.5 inches displacement, but do not necessarily represent the energy to failure unless noted.

Overall, there was no significant degradation due to the simulated laboratory exposure. It is noted that of the 20 Vendor "F" beams tested, eight experienced a complete failure, four Vendor "G" beams failed, and no Vendor "E" beams failed. (A laminate failure also being defined as a visible open crack in

the polycarbonate.) Complete failure indicates that the specimen was cracked completely in two pieces. Typical force versus displacement curves as shown for each vendor as Figures 25, 26, and 27 document the difference in stiffness of each of the candidate beams. In all cases, the acrylic outer ply failed in the area under the impactor.

Sixty flatwise tension specimens were tested to determine the ability of the candidate material to resist delamination. The ultimate tensile strength of the interlaminar layers for each condition, as well as the type of failure, is presented in Table 15. Typical load versus displacement curves are shown for each vendor in Figures 28, 29, and 30.

Sixty torsional shear specimens were tested to determine interlaminar shear strength of the candidate laminates. The shear strength for each condition is shown in Table 16. The simulated environmental conditioning had little effect on the shear force required to delaminate the material. A typical plot of each vendor's material of torque versus angular displacement is shown in Figures 31, 32, and 33. The differences in ultimate shear strength and relative stiffness are readily apparent from these plots. The type of failure also differed; both Vendors "E" and "G" exhibiting an adhesive type failure, in which the failure occurred between the outside ply and inner layer, and Vendor F exhibiting a cohesive type of failure within the interlayer itself.

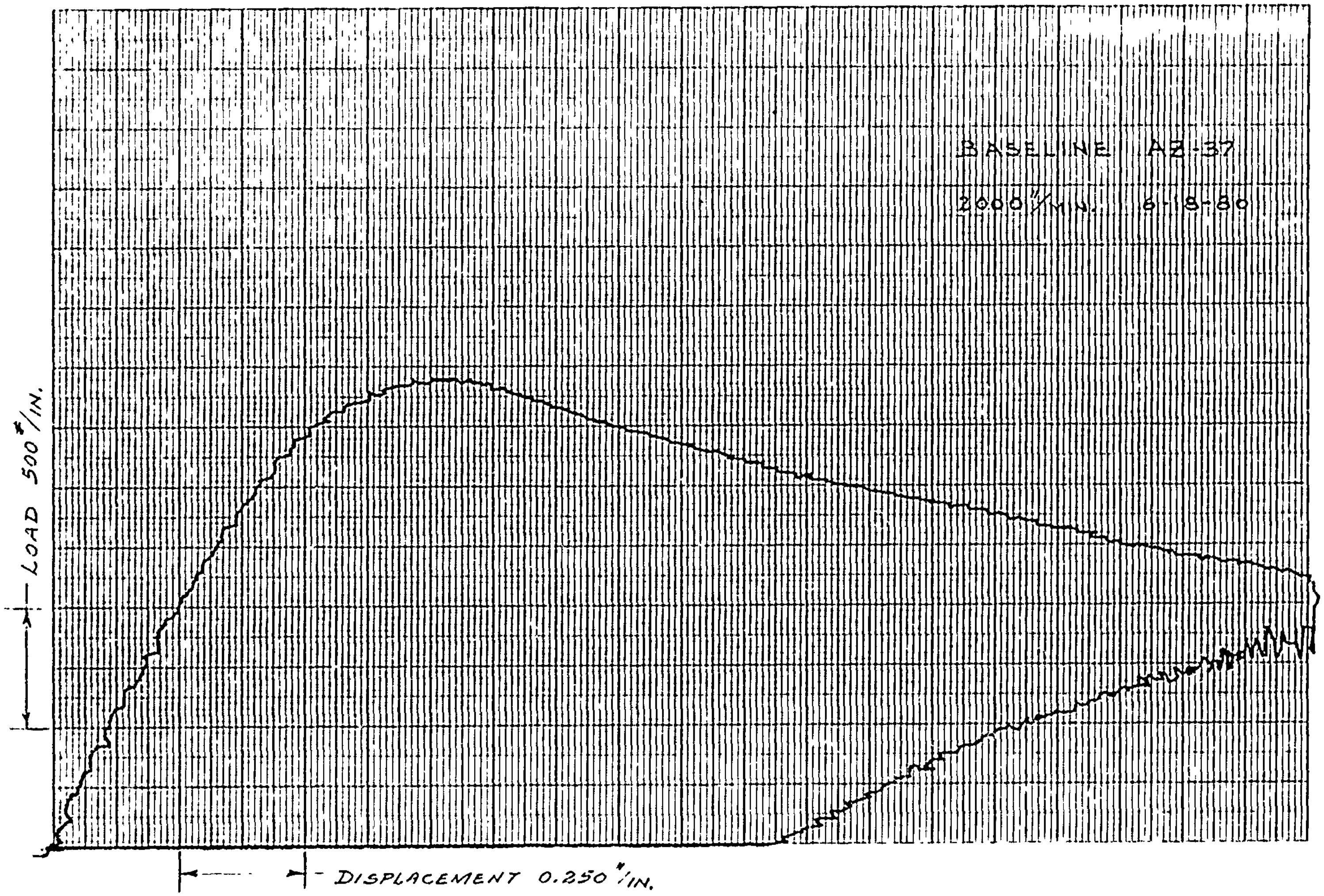


Figure 21. Typical Load vs. Displacement Plot; MTS Beam; Vendor "A".

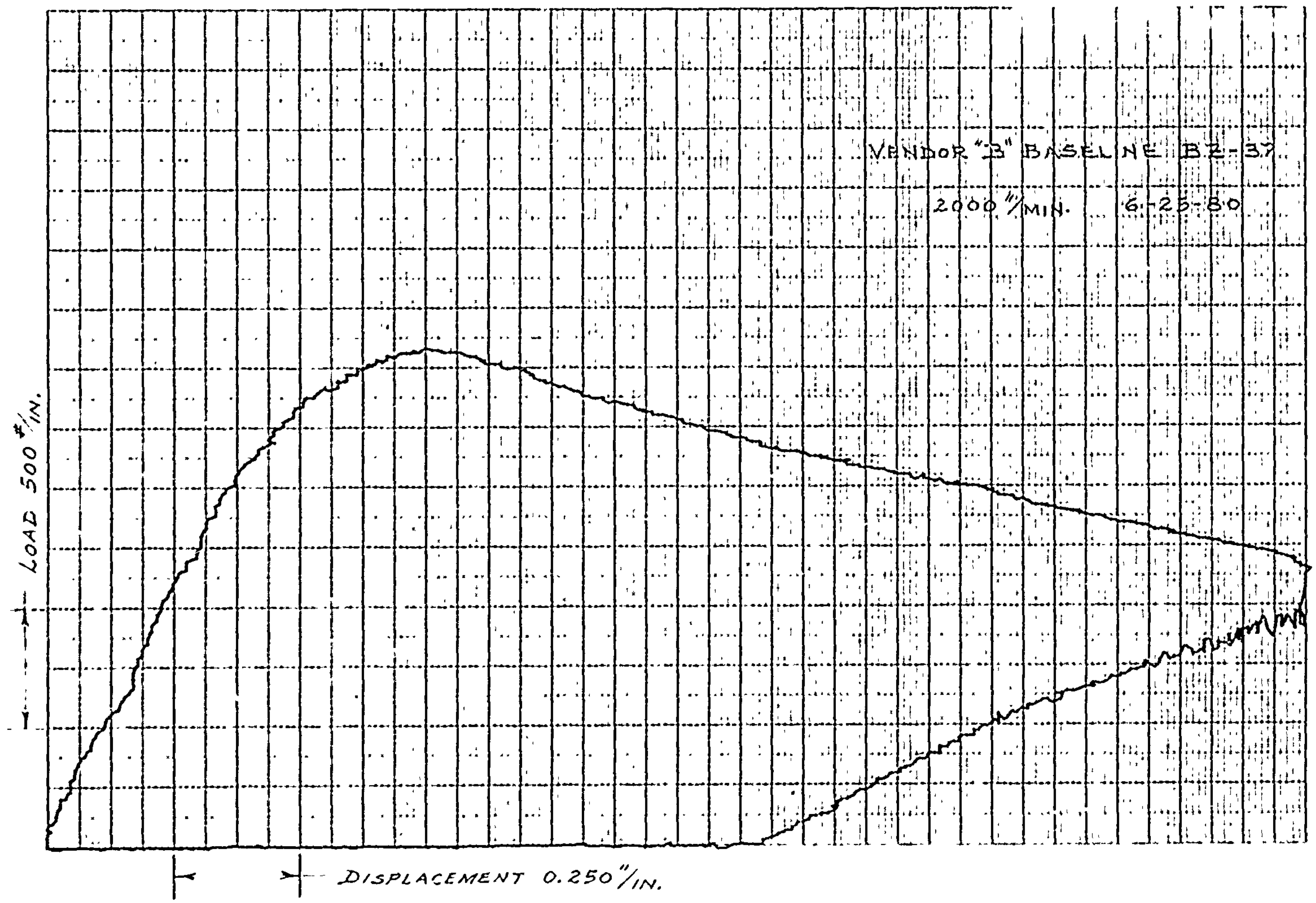


Figure 22. Typical Load vs. Displacement Plot; MTS Beam; Vendor "B".

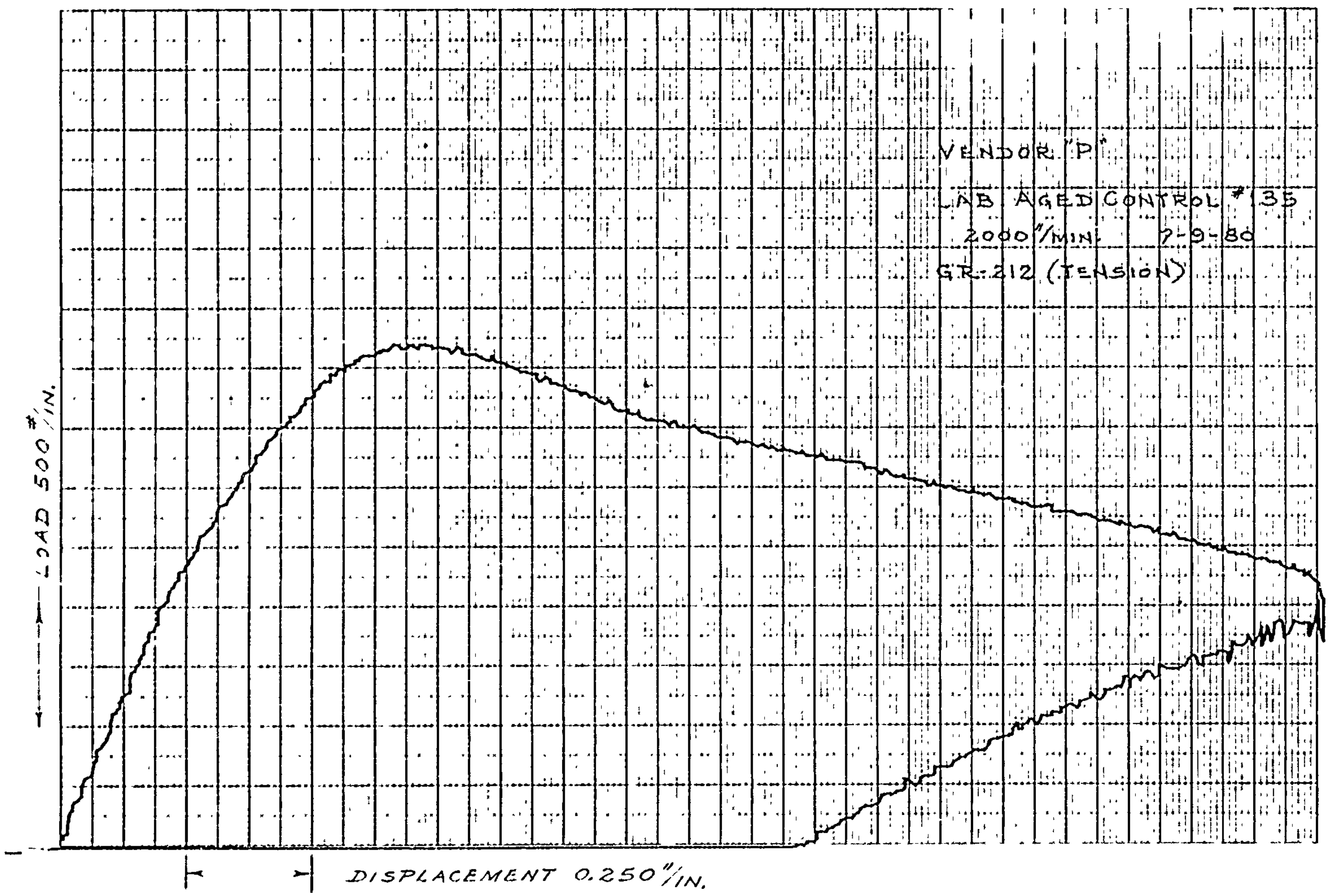


Figure 23. Typical Load vs. Displacement Plot; MTS Beam; Vendor "P" (GR212).

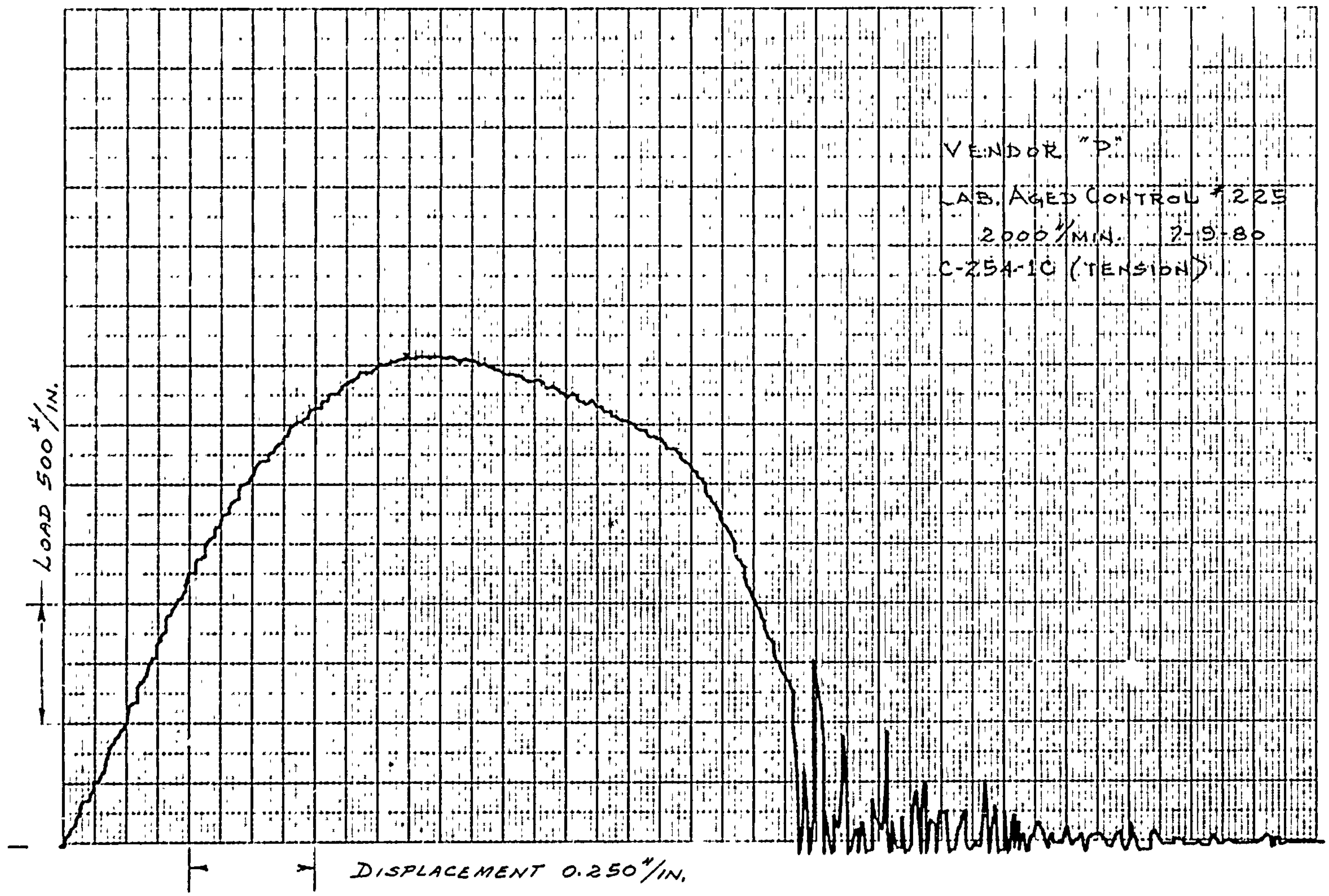


Figure 24. Typical Load vs. Displacement Plot; MTS Beam; Vendor "P" (C254-1C).

TABLE 5

MTS BEAM TEST RESULTS

VENDOR P

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
252	Baseline	155	F	
247		173	F	
128		196	F	
125		198	F	
84		162	F	
235		321	D	GR212
253		306	D	GR212
243		327	D	GR212
118		346	D	GR212
100		332	D	GR212
UN-1		316	D	Uncoated
UN-3		320	D	Uncoated
UN-5		322	D	Uncoated
UN-7		359	D	Uncoated
UN-9		360	D	Uncoated
182	Moisture 95% R.H., 2 wks.	182	F	
206		180	F	
203		181	F	
123		197	F	
119		178	F	
184	Moisture 95% R.H., 6 wks.	154	F	
200		164	F	
212		192	F	
161		184	F	
205		190	F	
246	Thermal 120°F, 6 wks.	180	F	
338		159	F	
284		164	F	
286		163	F	
282		143	F	

[1] F denotes specimen failure (tension surface)

D denotes ductile deformation below threshold of failure

[2] Coating C-254-1C tested in tension (opposite impact) unless otherwise noted.

TABLE 5 (continued)

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
385	200°F, 2 wks.	167	F	
387		166	F	
389		184	F	
393		203	F	
395		181	F	
239	Thermal Spike	205	F	
337	Thermal Spike	173	F	
137	UV-1 yr.	182	F	
218		172	F	
207		180	F	
164		190	F	
124		202	F	
219	UV-2 yr.	225	F	
129		230	F	
151		287	F	
172		230	F	
181		212	F	
197	UV-3 yr.	244	F	
179		246	F	
227		276	F	
158		233	F	
189		331	F	
155	UV-5 yr.	285	F	
169		316	F	
127		267	F	
175		249	F	
215		313	F	
149	UV-10 yr.	310	F	
163		411	F	
220		193	F	
176		254	F	
132		287	F	
336	UV/Humidity-1 yr.	195	F	
305		178	F	
292		170	F	
278		152	F	
258		178	F	
311	UV/Humidity-2 yr.	211	F	
281		211	F	
272		276	F	
267		236	F	
245		240	F	

TABLE 5 (continued)

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
328	UV/Humidity-3 yr.	206	F	
293		277	F	
299		331	D	
255		224	F	
285		295	F	
315	UV/Humidity-5 yr.	346	D	
300		274	F	
332		297	F	
263		319	F	
308		340	D	
234	UV/Humidity-10 yr.	335	D	
265		347	D	
316		329	F	
280		337	D	
298		331	D	
PZ 18	Temp./Humidity	160	F	
PZ 19		181	F	
PZ 20		147	F	
PZ 21		163	F	
PZ 22		184	F	
59	EMMA-1 yr.	69	F	
40		178	F	
50		166	F	
71		152	F	
79		175	F	
41	EMMA-2 yr.	166	F	
74		176	F	
63		29	F	
15		168	F	
29		351	D	
6	EMMA-3 yr.	52	F	
19		15	F	
39		179	F	
45		148	F	
56		20	F	
94	EMMA-5 yr.	11	F	
14		18	F	
3		21	F	

TABLE 5 (concluded)

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
10	EMMAQUA-1 yr.	187	F	
83		160	F	
26		167	F	
76		167	F	
69		173	F	
22	EMMAQUA-2 yr.	175	F	
12		166	F	
66		163	F	
90		165	F	
35		156	F	
54	EMMAQUA-3 yr.	142	F	
37		66	F	
25		167	F	
17		18	F	
77		16	F	
115	EMMAQUA-5 yr.	19	F	
109		22	F	
73		32	F	
180	Lab. Aged Control	166	F	
225		183	F	
135		319	D	GR212
168		314	D	GR212

TABLE 6

BEAM TEST RESULTS

VENDOR A

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Comment*
AZ 33	Baseline	303	D
AZ 34		298	D
AZ 35		302	D
AZ 36		301	D
AZ 37		299	D
AZ 38		294	D
AZ 45	Temp./Humidity	296	D
AZ 46		290	D
AZ 47		299	D
AZ 48		301	D
AZ 49		296	D
AZ 50		297	D
AZ 39	UV	300	D
AZ 40		303	D
AZ 41		301	D
AZ 42		299	D
AZ 43		302	D
AZ 44		305	D
AZ 51	Combined	295	D
AZ 52		292	D
AZ 53		285	D
AZ 54		294	D
AZ 55		295	D
AZ 56		286	D

*F denotes specimen failure (tension surface)

D denotes ductile deformation below threshold of failure

TABLE 7

MTS BEAM TEST RESULTS

VENDOR B

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Comment*
BZ 33	Baseline	318	D
BZ 34		322	D
BZ 35		329	D
BZ 36		325	D
BZ 37		319	D
BZ 38		326	D
BZ 45	Temp./Humidity	307	D
BZ 46		312	D
BZ 47		311	D
BZ 48		315	D
BZ 49		310	D
BZ 39	UV	187	F
BZ 40		320	D
BZ 41		173	F
BZ 42		162	F
BZ 43		189	F
BZ 44		290	F
BZ 51	Combined	180	F
BZ 52		316	D
BZ 53		312	D
BZ 54		146	F
BZ 55		259	F
BZ 56		317	D

*F denotes specimen failure (tension surface)

D denotes ductile deformation below threshold of failure

TABLE 8

FALLING WEIGHT IMPACT TEST RESULTS

VENDOR P

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
PZ 6	Baseline	175	F	
PZ 7		175	F	
PZ 8		175	P	
PZ 9		125	P	
PZ 10		125	D	
PZ 1		350	F	GR212
PZ 2		350	D	GR212
PZ 3		375	F	GR212
PZ 4		400	D	GR212
PZ 5		450	D	GR212
319		500	P	
162		300	P	
321		250	P	
294		150	P	
140		150	D	GR212
195		75	D	
310		100	P	
186		85	D	
189		100	D	
213		110	D	
303		125	P	
201		250	F	GR212
331		250	F	GR212
194		250	F	GR212
226		265	F	GR212
5		275	F	GR212
333		275	F	GR212
44		300	D	GR212
98		325	D	GR212
154		350	F	GR212
139		375	P	GR212
325		375	F	GR212
202		150	D	
241		175	P	

[1] D denotes ductile deformation below failure

F denotes threshold of failure; visible open crack

P denotes penetration; beam split in two; exceeds failure.

[2] Coating C-254-1C tested in tension (opposite impact) unless otherwise noted.

TABLE 8 (continued)

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
143		150	D	
277		175	P	
199		150	D	
145		175	F	
208		175	F	
210		175	F	
144		175	F	
UN 8		450	D	Uncoated
UN 6		550	D	Uncoated
UN 11		600	D	Uncoated
UN 12		650	D	Uncoated
	Moisture			
131	95% R.H., 2 wks.	100	D	
165		110	D	
170		110	D	
171		120	D	
192		120	D	
159		125	D	
229		140	D	
	Moisture			
187	95% R.H., 6 wks.	125	D	
142		140	D	
152		150	D	
216		150	D	
130		165	D	
133		150	D	
136		175	F	
	Thermal			
322	120°F, 6 wks.	175	F	
344		175	F	
276		175	P	
270		150	P	
291		150	P	
244		150	P	
240		125	P	
	Thermal			
397	200°F, 2 wks.	175	F	
383		150	F	
386		150	F	
388		175	P	
392		160	F	
394		160	F	
396		160	F	

TABLE 8 (continued)

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
254	Thermal Spike	150	P	
340	Thermal Spike	125	D	
122	UV-1 yr.	150	D	
222		175	F	
138		175	F	
209		175	F	
134		175	F	
185		175	F	
228	UV-2 yr.	175	D	
160		175	D	
188		175	D	
150		200	F	
198		200	F	
121		200	D	
178		200	F	
177	UV-3 yr.	200	D	
224		225	D	
196		225	D	
183		250	F	
204		250	F	
156		250	F	
230		265	F	
214	UV-5 yr.	250	D	
223		275	D	
193		300	D	
174		325	F	
126		325	F	
166		350	F	
148		350	P	
147	UV-10 yr.	325	D	
146		350	F	
221		350	F	
120		325	F	
141		350	F	
256	UV/Humidity-1 yr.	175	P	
295		175	P	
273		150	F	
317		150	F	
318		175	P	
341		150	F	
287		150	P	

TABLE 8 (continued)

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
304	UV/Humidity-2 yr.	150	D	
326		175	D	
274		200	F	
306		200	F	
264		225	F	
269		225	F	
233		250	F	
296	UV/Humidity-3 yr.	250	F	
307		260	F	
309		260	F	
238		260	F	
345		260	F	
290		275	F	
260		300	P	
312	UV/Humidity-5 yr.	325	F	
301		325	F	
339		325	F	
324		300	F	
279		300	F	
327		350	F	
261		325	F	
289	UV/Humidity-10 yr.	350	D	
313		375	F	
330		375	F	
232		375	P	
266		375	D	
PZ 11	Temp./Humidity	175	P	
PZ 12		200	P	
PZ 13		150	D	
PZ 14		175	F	
PZ 15		175	F	
PZ 16		175	F	
PZ 17		175	F	
80	EMMA-1 yr.	175	F	
64		175	P	
87		175	F	
20		175	F	
108		175	P	
93		175	P	
48		175	P	

TABLE 8 (concluded)

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)	Comment (2)
13	EMMA-2 yr.	175	P	
102		150	P	
101		175	P	
21		150	F	
32		150	F	
55		175	P	
65		150	F	
106	EMMA-3 yr.	75	P	
92	EMMA-3 yr.	50	D	
53	EMMA-5 yr.	75	P	
11		75	P	
42		75	P	
60	EMMAQUA-1 yr.	175	P	
91		150	F	
9		150	F	
23		175	F	
110		175	P	
70		150	P	
104		150	P	
97		150	F	
96	EMMAQUA-2 yr.	150	P	
8		150	P	
27		125	P	
82		150	P	
107		100	P	
46		75	P	
78	EMMAQUA-3 yr.	175	P	
114		150	P	
99		150	P	
105		125	P	
112		125	P	
7		75	P	
31	EMMAQUA-5 yr.	75	P	
28		75	P	
57		75	P	
153	Lab. Aged Control	175	F	
211		175	F	
157		350	F	GR212
117		350	F	GR212

TABLE 9

FALLING WEIGHT IMPACT TEST RESULTS

VENDOR A

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)
AZ 1	Baseline	550	D
AZ 2		600	D
AZ 3		600	D
AZ 22	Temp./Humidity	550	P
AZ 23		450	D
AZ 24		325	D
AZ 9	UV	500	P
AZ 10		400	D
AZ 11		475	D
AZ 12		500	D
AZ 13		525	P
AZ 14		500	P
AZ 15		475	D
AZ 16		500	P
AZ 26	Combined	550	D
AZ 27		600	P
AZ 28		575	P
AZ 29		550	P
AZ 31		550	D
AZ 58		500	D
AZ 59		525	D
AZ 60		575	P

[1] D denotes ductile deformation; below failure

F denotes threshold of failure; visible open crack

P denotes penetration; beam split in two; exceeds failure

TABLE 10

FALLING WEIGHT IMPACT TEST RESULTS

VENDOR B

Specimen Number	Exposure Condition	Energy, Ft-Lbs.	Failure (1)
BZ 5	Baseline	475	F
BZ 6		475	D
BZ 7		475	D
BZ 8		500	D
BZ 58		450	D
BZ 59		550	P
BZ 60		500	P
BZ 61		450	D
BZ 17	Temp./Humidity	400	D
BZ 18		500	P
BZ 19		450	D
BZ 20		475	P
BZ 21		475	D
BZ 22		475	D
BZ 23		475	D
BZ 24		500	D
BZ 9	UV	200	F
BZ 10		200	D
BZ 11		200	F
BZ 12		250	F
BZ 13		300	P
BZ 14		250	D
BZ 15		250	P
BZ 16		225	P
BZ 25	Combined	225	P
BZ 26		200	F
BZ 27		200	F
BZ 28		225	P
BZ 29		200	P
BZ 30		175	D
BZ 31		200	F
BZ 62		200	P

1

D denotes ductile deformation; below failure

F denotes threshold of failure; visible open crack

P denotes penetration; beam split in two; exceeds failure

TABLE 11

AIR CANNON TEST RESULTS

VENDOR P

Specimen Number	Exposure Condition	Velocity Ft/Sec	Failure (1)	Comment (2)
346	Baseline	555	D	GR212
353		622	D	GR212
358		655	F	GR212
365		623	F	GR212
370		602	F	GR212
351		195	F	
354		142	D	
361		175	D	
367		196	F	
371		188	D	
UN-13		917	D	Uncoated
UN-14		1024	F	Uncoated
369	EMMA-1 yr.	146	F	
373		134	D	
374		140	D	
375		151	D	
376		172	D	
377	EMMAQUA-1 yr.	172	F	
378		164	D	
379		182	D	
380		196	D	
381		229	F	
348	UV-1 yr.	188	F	
352		178	F	
357		164	D	
364		193	D	
372		215	D	

[1]F denotes specimen failure exceeding threshold

D denotes ductile deformation below failure threshold

[2]Coating C-254-1C tested opposite impact unless otherwise noted

TABLE 12

CHEMICAL CRAZE TEST RESULTS

Specimen Number and Vendor	Aging Conditions	Solvent	Failure/ Total Time	Observations
AY-1	Baseline	Isopropyl Alcohol	30 Minutes	No crazes or visible effects
AY-2	Baseline	Isopropyl Alcohol	30 Minutes	No crazes or visible effects
BY-1	Baseline	Isopropyl Alcohol	30 Minutes	No crazes or visible effects
BY-2	Baseline	Isopropyl Alcohol	30 Minutes	No crazes or visible effects
PY-1	Baseline	Isopropyl Alcohol	30 Minutes	No crazes or visible effects
PY-2	Baseline	Isopropyl Alcohol	30 Minutes	No crazes or visible effects
AY-3	Baseline	Ethylene Glycol	30 Minutes	No crazes or visible effects
AY-4	Baseline	Ethylene Glycol	30 Minutes	No crazes or visible effects
BY-3	Baseline	Ethylene Glycol	30 Minutes	No crazes or visible effects
BY-4	Baseline	Ethylene Glycol	30 Minutes	No crazes or visible effects
PY-3	Baseline	Ethylene Glycol	30 Minutes	No crazes or visible effects
PY-4	Baseline	Ethylene Glycol	30 Minutes	No crazes or visible effects
AY-9	2 yr. UV	Ethylene Glycol	30 Minutes	No crazing or visible effects
AY-10	2 yr. UV	Ethylene Glycol	30 Minutes	No crazing or visible effects
BY-9	2 yr. UV	Ethylene Glycol	30 Minutes	No crazing or visible effects
BY-10	2 yr. UV	Ethylene Glycol	30 Minutes	No crazing or visible effects
PY-9	2 yr. UV	Ethylene Glycol	30 Minutes	No crazing or visible effects
PY-10	2 yr. UV	Ethylene Glycol	30 Minutes	No crazing or visible effects
AY-15	2 yr. Temp/	Ethylene Glycol	30 Minutes	No crazing or visible effects
AY-16	Hum. (120°F)	Ethylene Glycol	30 Minutes	No crazing or visible effects
BY-15	2 yr. Temp/	Ethylene Glycol	30 Minutes	No crazing or visible effects
BY-16	Hum. (120°F)	Ethylene Glycol	30 Minutes	No crazing or visible effects
PY-15	2 yr. Temp/	Ethylene Glycol	30 Minutes	No crazing or visible effects
PY-16	Hum. (120°F)	Ethylene Glycol	30 Minutes	No crazing or visible effects

TABLE 12 (continued)

Specimen Number and Vendor	Aging Conditions	Solvent	Failure/ Total Time	Observations
AY-7	2 yr. UV	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
AY-8	2 yr. UV	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
BY-7	2 yr. UV	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
BY-8	2 yr. UV	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
PY-7	2 yr. UV	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
PY-8	2 yr. UV	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
AY-13	2 yr. Temp/	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
AY-14	Hum. (120°F)	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
BY-13	2 yr. Temp/	Isopropyl Alcohol	30 Minutes	No crazes; slight discoloration
BY-14	Hum. (120°F)	Isopropyl Alcohol	30 Minutes	& softening of coating
PY-13	2 yr. Temp/	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
PY-14	Hum. (120°F)	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
AY-19	Combined Agings	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
AY-20	(R.T. Hum/UV)	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
BY-19	Combined Agings	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
BY-20	(R.T. Hum/UV)	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
PY-19	Combined Agings	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
PY-20	(R.T. Hum/UV)	Isopropyl Alcohol	30 Minutes	No crazing or visible effects
AY-21	Combined Agings	Ethylene Glycol	30 Minutes	No crazing or visible effects
AY-22	(R.T. Hum/UV)	Ethylene Glycol	30 Minutes	No crazing or visible effects
BY-21	Combined Agings	Ethylene Glycol	30 Minutes	No crazing or visible effects
BY-23	(R.T. Hum/UV)	Ethylene Glycol	30 Minutes	No crazing or visible effects
PY-21	Combined Agings	Ethylene Glycol	30 Minutes	No crazing or visible effects
PY-22	(R.T. Hum/UV)	Ethylene Glycol	30 Minutes	No crazing or visible effects

TABLE 12 (continued)

Specimen Number and Vendor	Aging Conditions	Solvent	Failure/ Total Time	Observations
AY-5	Baseline	MEK	30 Minutes	Coating is deformed & slightly discolored; small crazes (1/32") under patch area
AY-6	Baseline	MEK	30 Minutes	
*BY-5	Baseline	MEK	48 Seconds	Complete failure
*BY-6	Baseline	MEK	30 Minutes	Coating is discolored; peeled & cracked
PY-5	Baseline	MEK	30 Minutes	No discoloring or deformation of coating; very slight crazing
PY-6	Baseline	MEK	30 Minutes	
**BY-1	Baseline	MEK	30 Minutes	Large crazes (1/2") first craze @ 9':17";
**BY-2	Baseline	MEK	30 Minutes	First craze @ 8':20"; coating swelled & discolored
AY-11	2 yr. UV	MEK	30 Minutes	Coating deforms; slightly small crazing in polycarbonate
AY-12	2 yr. UV	MEK	30 Minutes	
BY-11	2 yr. UV	MEK	30 Minutes	Slight dissolving of coating; numerous small crazings; first craze @ 5':09"
BY-12	2 yr. UV	MEK	30 Minutes	Large craze & numerous small crazes
PY-11	2 yr. UV	MEK	30 Minutes	No discoloration of coating: very slight crazing
PY-12	2 yr. UV	MEK	30 Minutes	
AY-17	2 yr. Temp/ Hum.(120°F)	MEK	9':30"	Large craze appeared @ 1':40"
AY-18		MEK	30 Minutes	Numerous small crazings into polycarbonate; slight discoloration of coating
BY-17	2 yr. Temp/ Hum.(120°F)	MEK	30 Minutes	6':45" crazing appeared; large 3/8" deep crazes formed
BY-18	2 yr. Temp/ Hum. (120°F)	MEK MEK	17':30"	9 min. crazes formed; complete failure
PY-17	2 yr. Temp/ Hum. (120°F)	MEK	30 Minutes	Dissolving & slight discoloring or surface; 20 min. small crazing appeared; numerous small crazes, both specimens
PY-18		MEK	30 Minutes	

TABLE 12 (concluded)

Specimen Number and Vendor	Aging Conditions	Solvent	Failure/ Total Time	Observations
AY-23 AY-24	Combined Agings (R.T. Hum/UV)	MEK MEK	30 Minutes 30 Minutes	2':30" small crazing appeared: dissolving & discoloration of coating; numerous small crazes both specimens
BY-23 BY-24	Combined Agings (R.T. Hum/UV)	MEK MEK	30 Minutes 30 Minutes	21 min. small crazing appeared; very few small crazes
PY-23 PY-24	Combined Agings (R.T. Hum/UV)	MEK MEK	30 Minutes 30 Minutes	Very slight surface cracks; very small

NOTES:

* BY-5, BY-6 were tested using FTM406, Method 6053. This method was abandoned and MIL-P-83310A method was used on all other tests.

** BY-1, BY-2 were tested again, after initial testing with alcohol, using MEK in the second test. Observations after first test showed no apparent effects, an effort was made to obtain reasonable data using MIL-P-83710A method.

Temperature and humidity agings were run at 95% ± 5% relative humidity and 120°F (49°C).

Combined agings were run at 95% ± 5% relative humidity at room temperature, plus UV exposure.

TABLE 13

ABRASION TEST RESULTS

PERCENT HAZE

	STROKES	VENDOR A	VENDOR B	VENDOR P
BASELINE (1-5)	0	2.74	1.56	2.17
	50	8.20	25.23	10.62
	100	16.76	31.83	17.51
	150	19.82	36.23	16.94
	300	29.03	50.19	22.26
2 Yr. U. V. (6-10)	0	3.59	2.55*	2.05*
	50	18.58	15.07*	11.86*
	100	20.59	20.25*	13.08*
	150	22.88	26.18*	16.51*
	300	28.02	34.72*	20.89*
2 Yr. Temp/Hum. (11-15)	0	3.69	3.72	2.70
	50	20.67	30.33	19.81
	100	24.77	42.11	19.03
	150	28.49	48.88	20.88
	300	38.34	63.27	30.46
2 Yr. Combined	0	3.24*	1.73*	2.13
	50	21.66*	25.93*	14.25
	100	27.94*	28.99*	14.86
	150	33.38*	34.28*	15.96
	300	43.79*	47.70*	21.22

NOTES: All data above is the average of the five samples per set except as noted by an *. The samples with an * are the average of four because of oversize machining, thereby not being acceptable to the sample holder of the Bayer Abrader.

All samples were abraded a total of 150 cycles (300 strokes) per minute, using a four-inch stroke. One kilogram of 6/14 quartz silica sand was discarded after each specimen test.

TABLE 14

MTS BEAM TEST RESULTS (FT. LBS.)

		Vendor					
Specimen	Exposure Condition	EZ	Average	FZ	Average	GZ	Average
1	Baseline	197		255 F*		424	
2		201		268		431	
3		201	201	236 F	253	266	395
4		202		273		424	
5		204		235 F		432	
6	3-yr. UV	200		277		388	
7		202		278		167	
8		202	202	278	281	433 F	361
9		206		277		386	
10		200		295		431	
11	Temp./Humidity	198		277		336 F	
12		201		283		374	
13		201	200	279 F	270	412	383
14		199		232 F		421	
15		199		281		371	
16	200°F/2 wk.	-		174 F		445	
17		-		292		444	
18		218	219	260 F	238	392	431
19		219		295		431 F	
20		219		170 F		441	

*F denotes failure.

TABLE 15

FLATWISE TENSION TEST RESULTS (PSI)

Specimen	Exposure Condition	EV	Average	FV	Average	GV	Average
		Vendor					
1	Baseline	2270 A*		575 C**		2425 P***	
2		2370 A		600 C		2675 P	
3		2165 A	2297	550 C	566	2725 P	2720
4		2395 A		540 C		2900 A	
5		2285 A		565 C		2875 P	
6	3-yr. UV	-		574 C		2800 P	
7		2255 A		-		2985 A	
8		2280 A	2275	552 C	570	2330 C	2721
9		2280 A		589 C		2985 A	
10		2286 A		563 C		2505 P	
11	Temp./Humidity	2280 A		565 C		2250 A	
12		2300 A		550 C		2530 P	
13		2325 A	2268	579 C	561	2715 A	2612
14		2220 A		569 C		2715 A	
15		2215 A		541 C		2850 P	
16	200°F/2 wk.	2300 A		598 C		2410 P	
17		2565 A		600 C		2410 P	
18		2565 A	2512	580 C	592	2500 P	2526
19		2505 A		601 C		2810 A	
20		2625 A		581 C		2500 A	

*A - Adhesive failure on acrylic surface.
**C - Cohesive type failure.
***P - Adhesive failure on polycarbonate surface.

TABLE 16

TORSIONAL SHEAR TEST RESULTS (PSI)

Specimen	Exposure Condition	Vendor EU	Average	Vendor FU	Average	Vendor GU	Average
1	Baseline	1000 A*		342 C**		2388 A	
2		1109 A		348 C		2388 A	
3		1064 A	994	340 C	346	2338 A	2339
4		983 A		354 C		2304 A	
5		815 A		346 C		2276 A	
6	3-yr. UV	885 A		357 C		2332 A	
7		941 A		354 C		2950 A	
8		836 A	910	351 C	349	2245 A	2402
9		955 A		343 C		2289 A	
10		931 A		338 C		2192 A	
11	Temp./Humidity	871 A		352 C		2445 A	
12		829 A		362 C		2501 A	
13		899 A	856	382 C	364	2585 A	2501
14		850 A		361 C		2529 A	
15		829 A		365 C		2445 A	
16	200°F/2 wk.	976 A		369 C		2501 A	
17		892 A		382 C		2490 A	
18		906 A	905	382 C	374	2557 A	2482
19		815 A		351 C		2388 A	
20		934 A		388 C		2473 A	

*A - Adhesive failure on acrylic surface
**C - Cohesive type failure

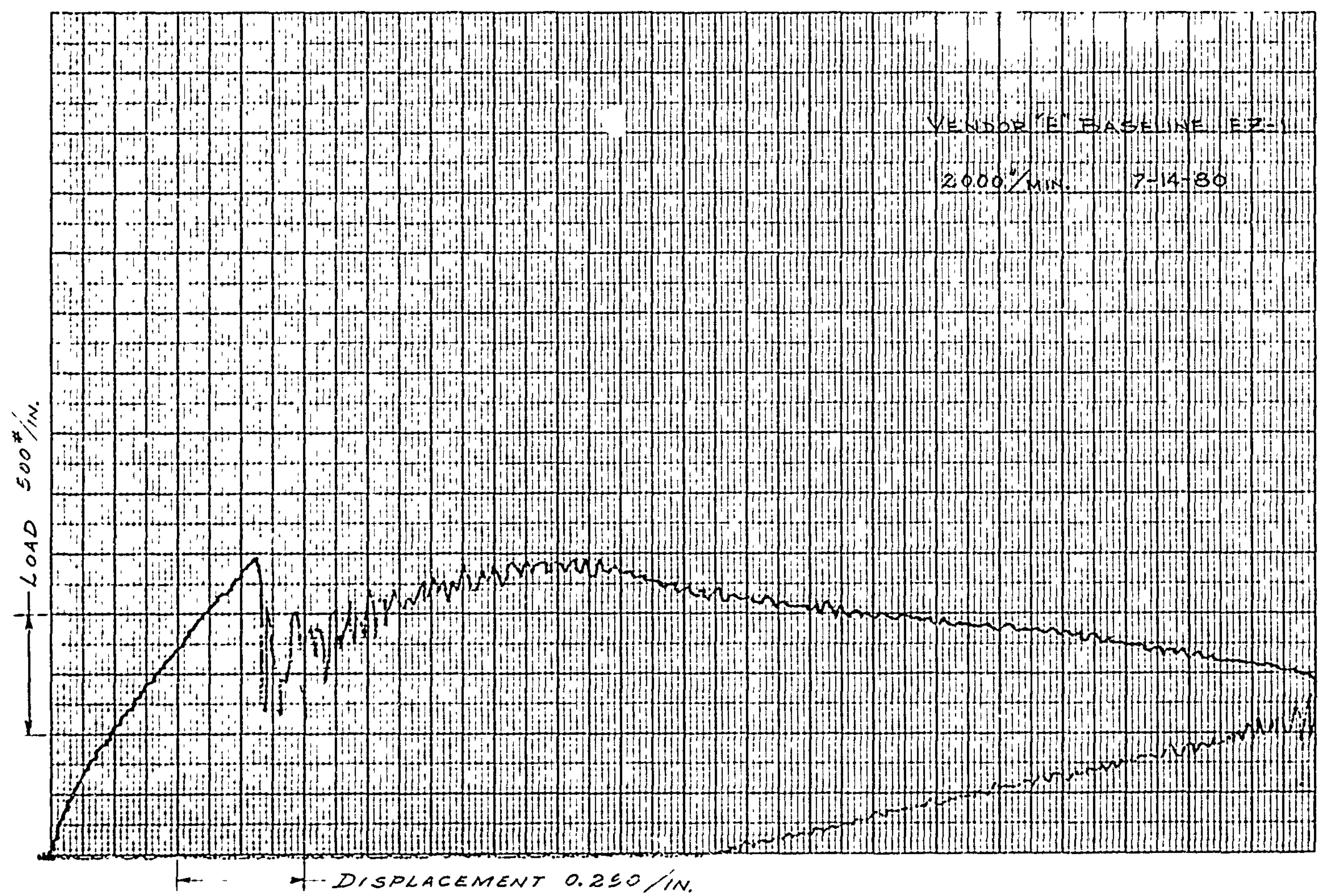


Figure 25. Typical Load vs. Displacement Plot; MTS Beam; Vendor "E".

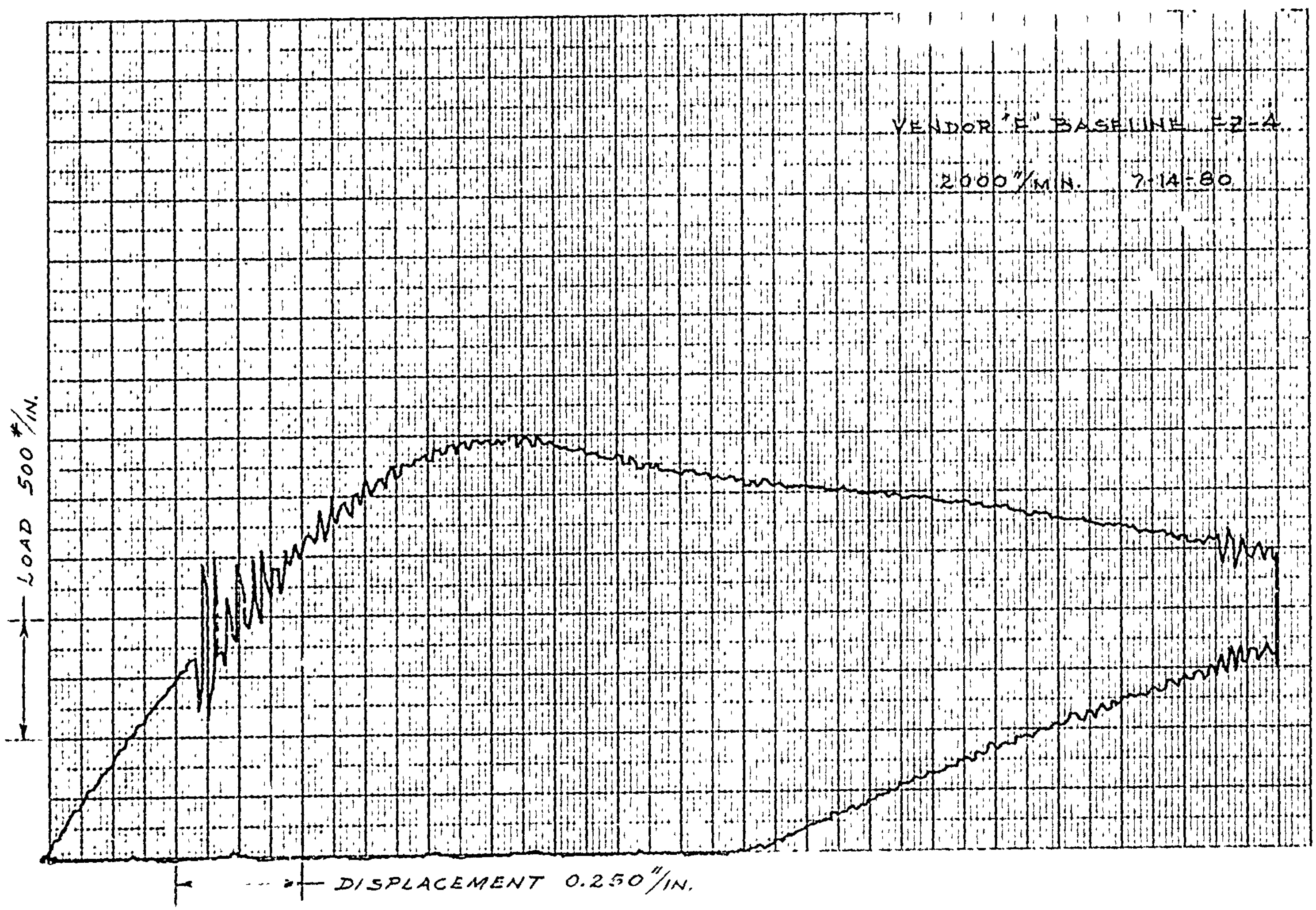


Figure 26. Typical Load vs. Displacement Plot; MTS Beam; Vendor "F".

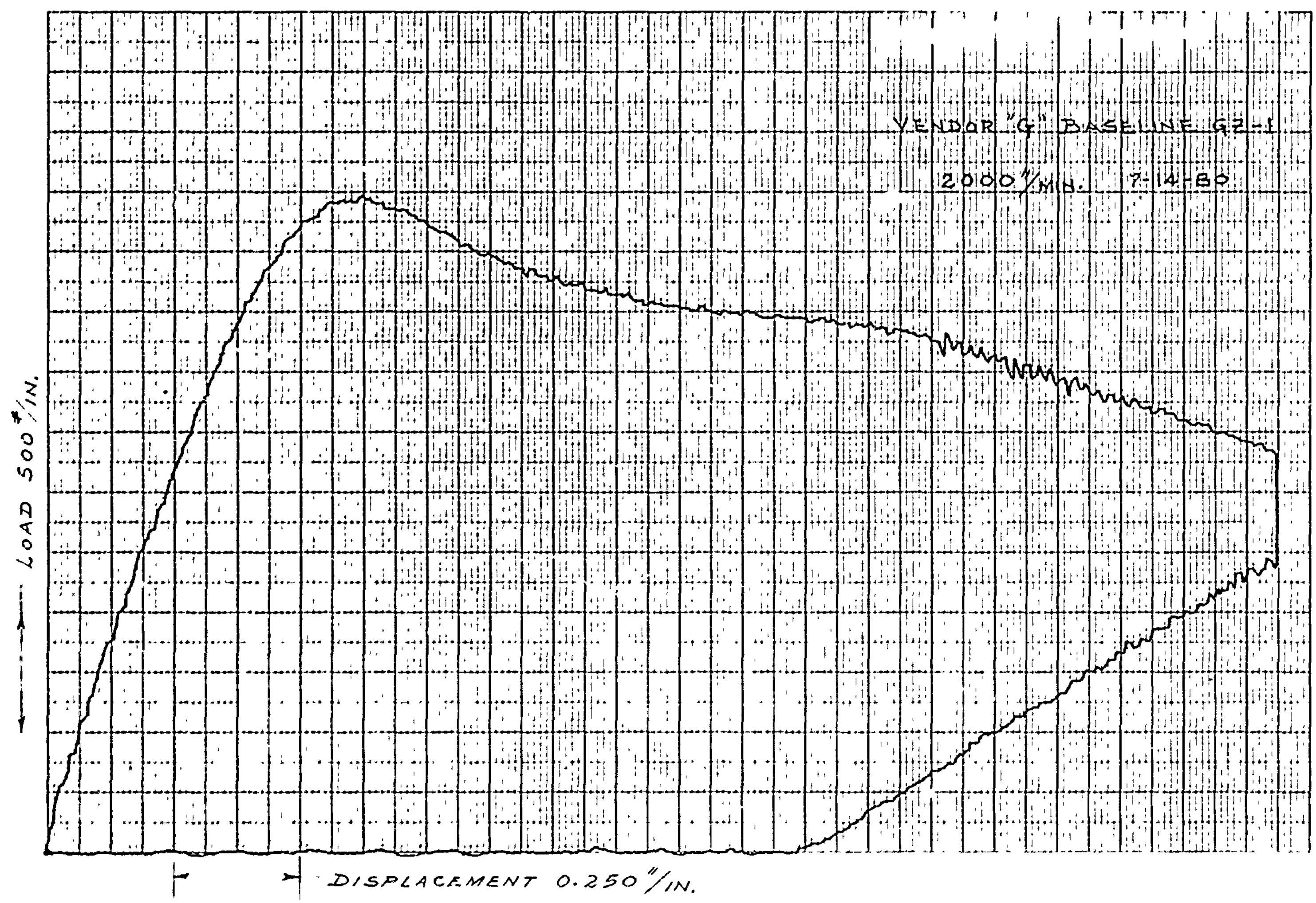


Figure 27. Typical Load vs. Displacement Plot; MTS Beam; Vendor "G".

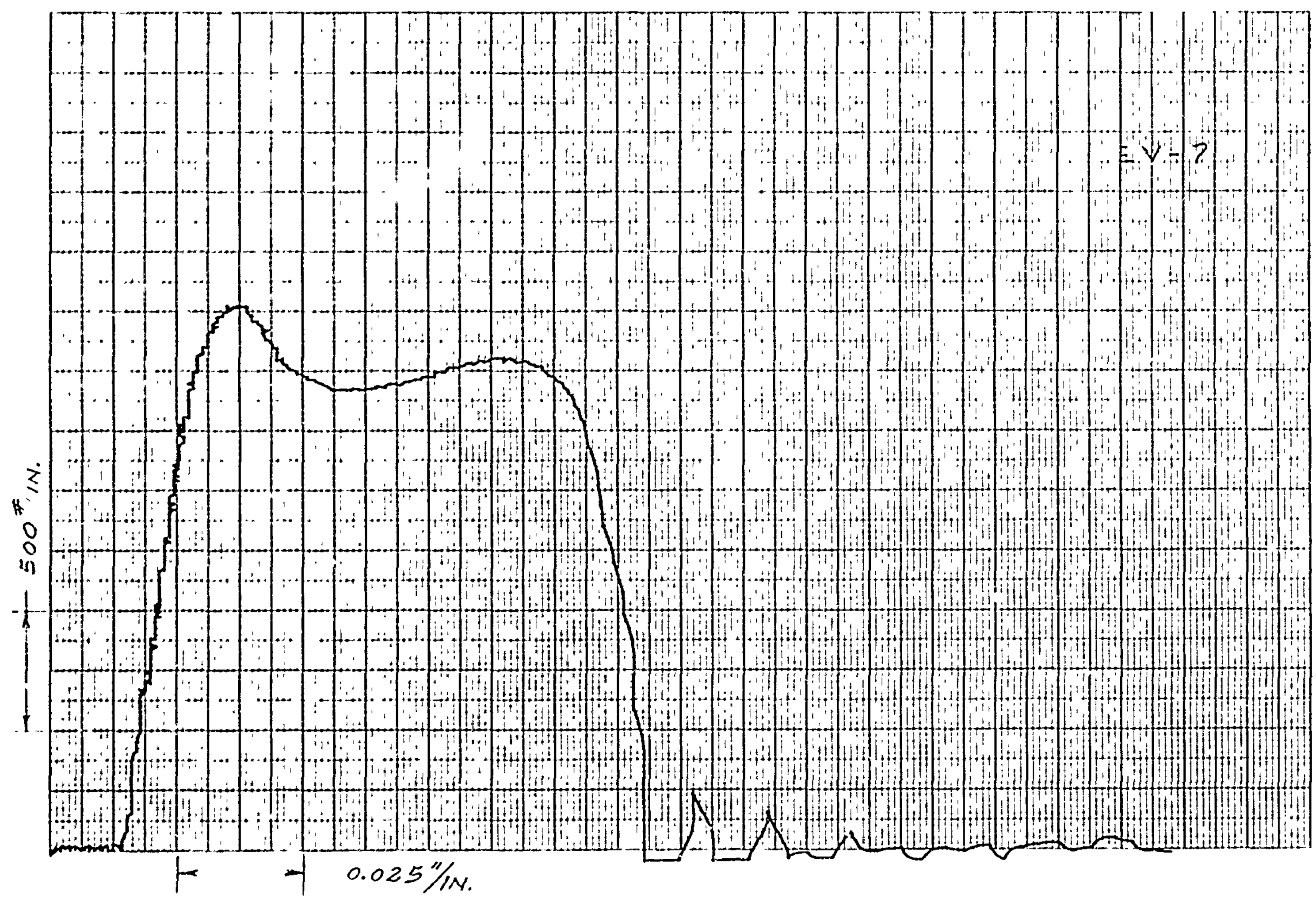


Figure 28. Typical Load vs. Displacement Plot; Flatwise Tension; Vendor "E".

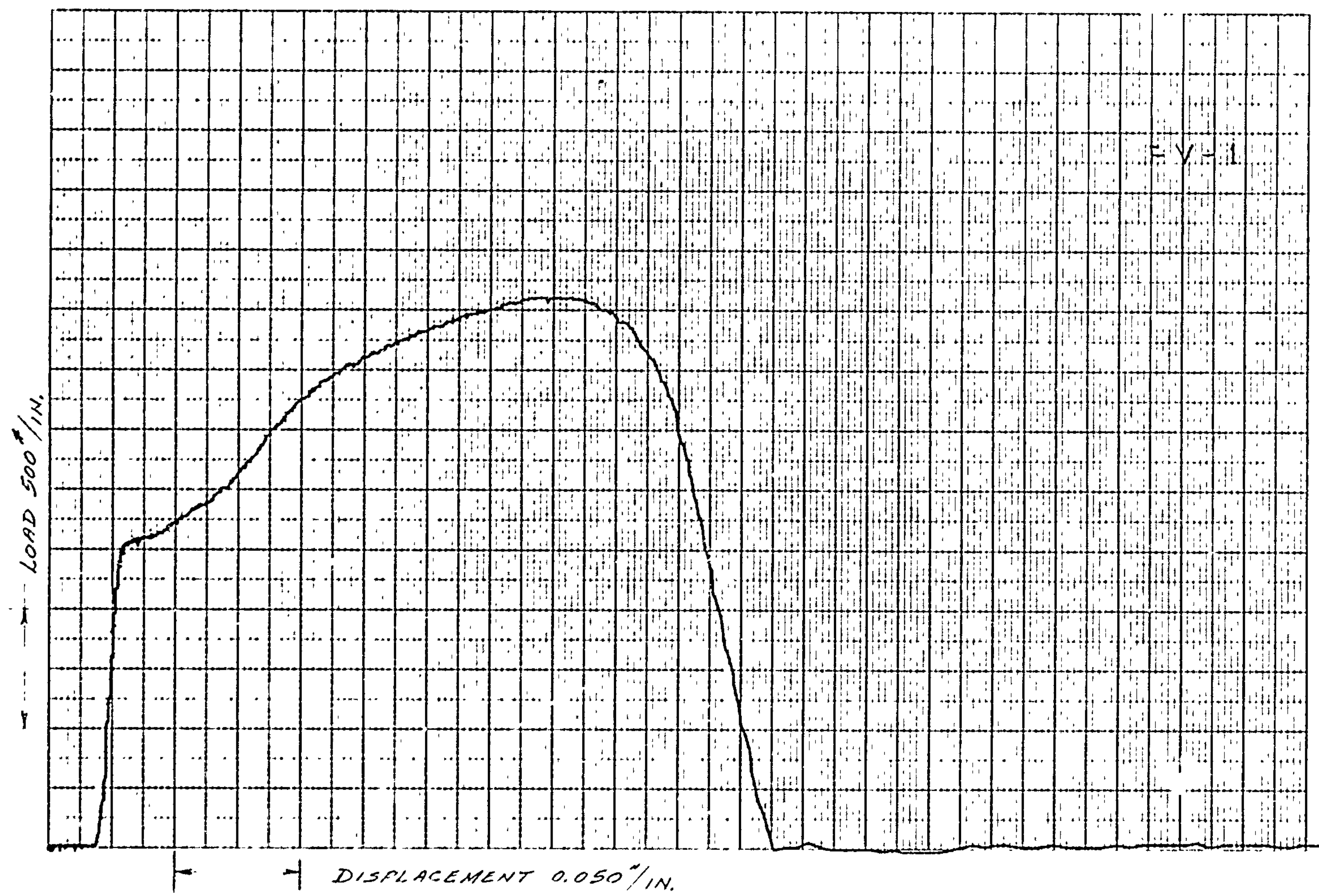


Figure 29. Typical Load vs. Displacement Plot; Flatwise Tension; Vendor "F".

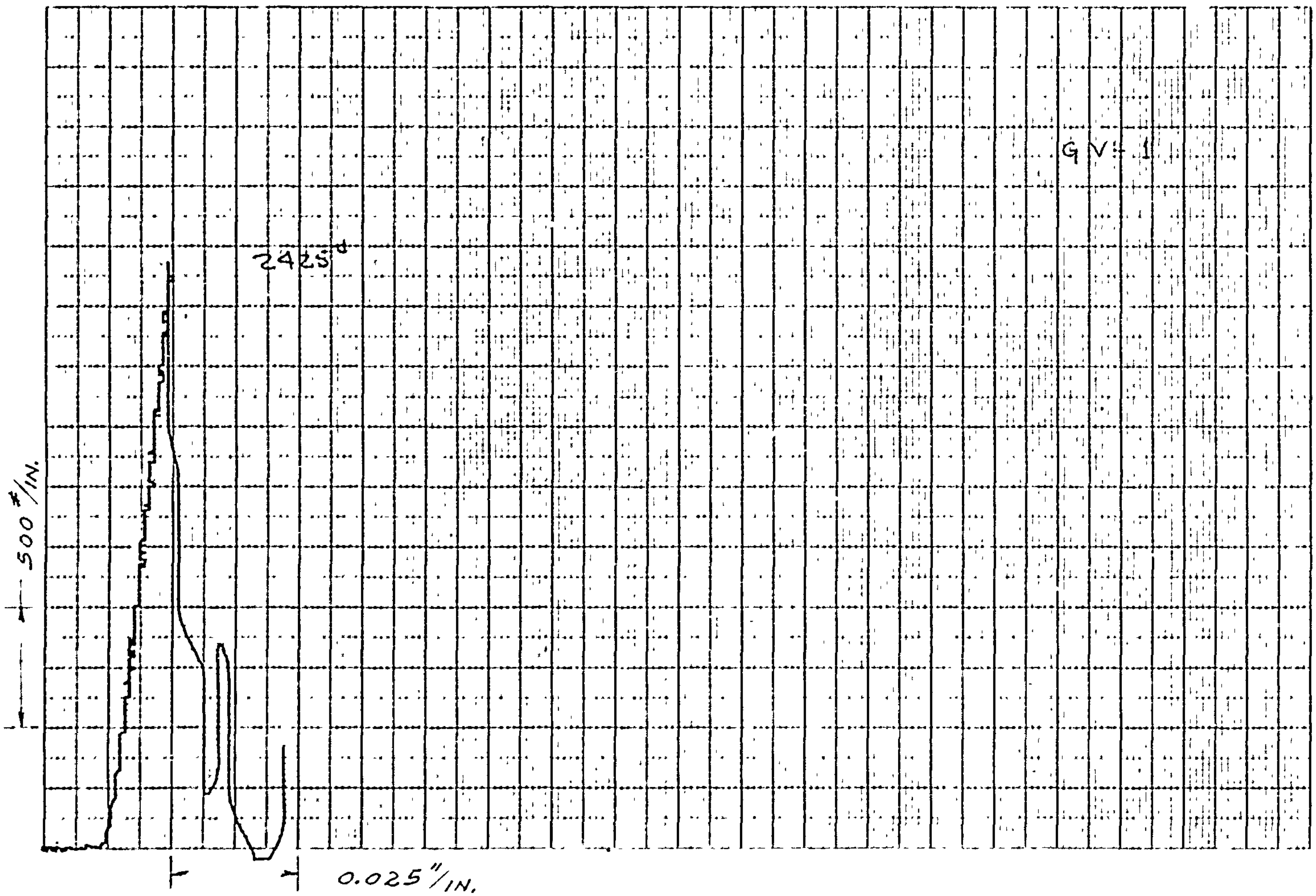


Figure 30. Typical Load vs. Displacement Plot; Flatwise Tension; Vendor "G".

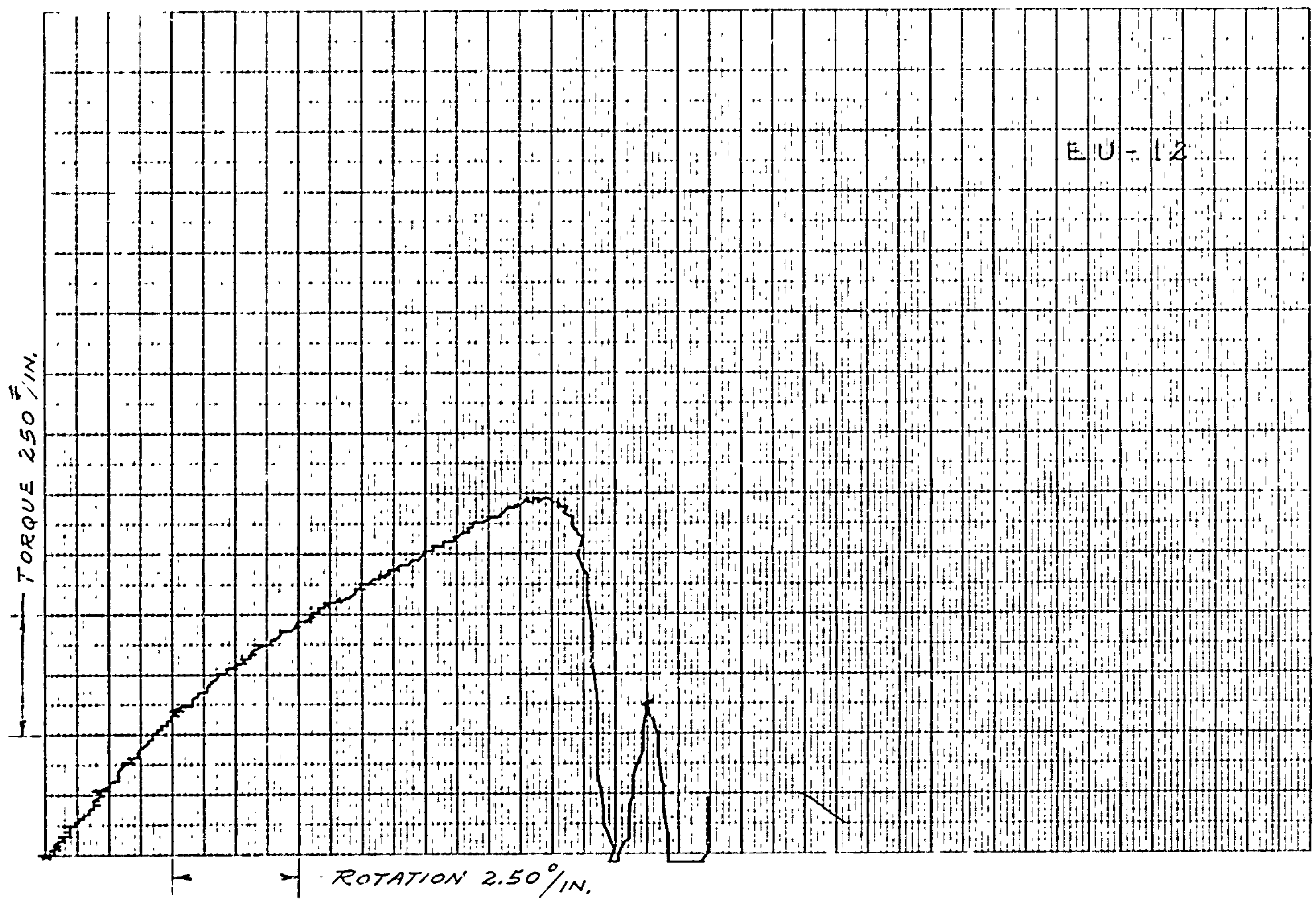


Figure 31. Typical Torque vs. Angular Displacement Plot; Torsional Shear; Vendor "E".

Figure 32. Typical Torque vs. Angular Displacement Plot; Torsional Shear, Vendor "F".

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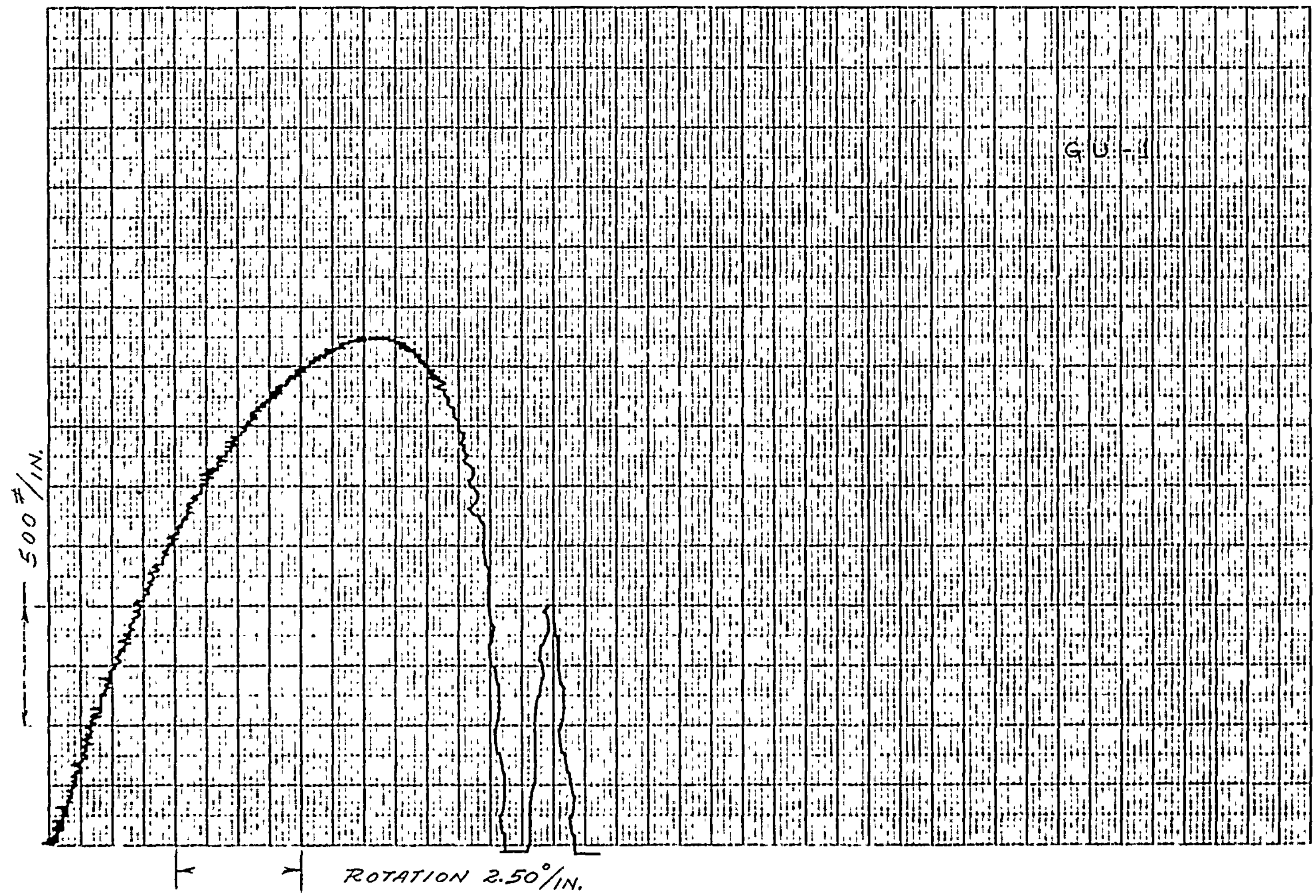


Figure 33. Typical Torque vs. Angular Displacement Plot; Torsional Shear; Vendor "G".

SECTION III
DISCUSSION OF RESULTS

Average data from MTS beam tests and threshold-of-failure data from falling weight impact tests are summarized in Table 17 for Vendor P monolithic coated polycarbonate and presented in bar graph form for comparison in Figures 34 and 35. For the MTS beam tests conducted at a fixed maximum displacement of 2.50 inches and the falling weight beam impact tests, a loading energy level of approximately 175 ft-lbs. was required to fail the critical tension loaded C-254-1C coated surface of baseline production F-16 (Vendor P) specimens; both Vendor A and Vendor B specimens indicating relatively higher baseline strength. Direct comparison of these individual tests indicates which material and conditioning combinations are grossly superior to others. A high level of certainty exists in the recorded values for threshold-of-failure data. However, for specimens tested below the threshold-of-failure energy level, all that is known is that each withstood the recorded load level with no indication as to what higher loading would be required to fail the specimen. Temperature and/or humidity conditioning had little effect on the test specimens. Laboratory accelerated ultraviolet radiation exposure of Vendor P material resulted in an unexpected increase in impact resistance as shown in Figure 36; conflicting with accelerated outdoor sunshine exposure (EMMA and EMMAQUA) which resulted in a sharp decrease in impact strength accompanied by embrittlement of the test samples. Based on falling weight energy to failure, two years of EMMAQUA exposure reduced the baseline impact resistance of Vendor P material by more than 50 percent.

Photographs of typical MTS and falling weight beam specimens, after test, are presented in Figures 37, 38, and 39. Visual inspection showed a deformation response typical of a ductile material undergoing simple three-point beam loading. Visual appearance of the C-254-1C coated surface of Vendor P beams after failure indicates the presence of fairly straight transverse cracks, spaced at even intervals across the impact test zone. The cracks are very shallow in the coating at the outboard

regions of the specimen loading area. Toward the center of the test region, the cracks deepen into the substrate, with critical cracks deepening into fissure openings in the polycarbonate (Reference Figure 40). Figure 41 shows a photomicrograph cross-section of the C-254-1C coated surface.

The visual appearance of the Vendor A coating remained similar for all tests and conditioning. Whether or not structural failure occurred, the coated surface remained virtually flawless and glassy smooth except in the immediate area of the failure. Figure 42 shows a photomicrograph cross-section of the Vendor A coated surface.

The visual appearance of the Vendor B coating exhibited more variability than either Vendor A or Vendor P material. In some instances after test, the surface had a smoothly flowed and virtually flawless appearance similar to that of Vendor A coating (Reference Figure 43). Other specimens produced shallow cracks in fairly transverse, straight, and continuous lines with fairly even spacing. Some baseline beams exhibited an appearance which was different from all others and appeared to have a split membrane skin, partially peeled from the polycarbonate, with a diamond shape appearing as the peeling progresses longitudinally while the split lengthens transversely. Many such small diamonds appear to develop simultaneously across the width of the coated surface. As each split lengthens transversely, these split lines link together to form a continuous split line across the specimen, with peeling of the coating on both sides of the split line; split lines being closer spaced toward mid-span. Figure 44 shows a photomicrograph cross-section of this Vendor B coated surface.

Based on the chemical craze and abrasion tests conducted on the three candidate coated monolithic polycarbonate materials, the production (Vendor P) specimens demonstrated the relatively best performance. As shown in the Appendix, the Vendor B coating demonstrated the relatively best resistance to the test rain erosion conditions.

Based on a limited number of tests conducted on three candidate laminate materials, no significant degradation resulted from thermal, moisture, or ultraviolet exposure. Differences in beam stiffness, flatwise tensile strength, and torsional shear strength were dependent on interlayer material. Figure 45 shows typical failed flatwise tension specimens fabricated from Vendor E, F, and G laminated polycarbonate material.

TABLE 17

TEST DATA SUMMARY
(Vendor P)

PRODUCTION F-16 MONOLITHIC COATED POLYCARBONATE

	Falling Weight Failure Threshold (ft-lbs)	MTS (2000 in/min) Energy (ft-lbs)
BASELINE		
GR212 in tension	350	327
C-254-1C in tension	175	177
Uncoated polycarbonate	>500	335
UV RADIATION (C-254-1C in tension)		
1-yr	175	185
2-yr	200	236
3-yr	250	266
5-yr	325	286
10-yr	340	291
MOISTURE (C-254-1C in tension)		
95% R.H. 2 wks.	>140	183
95% R.H. 6 wks.	175	177
THERMAL (C-254-1C in tension)		
120°F 6 wks.	175	162
200°F 2 wks.	160	180
120°F/250°F Spike	>125	189
EMMAQUA (C-254-1C in tension)		
1-yr	150	171
2-yr	Brittle fracture at 75 and above	165
3-yr	Brittle fracture at 75 and above	155
5-yr	Brittle fracture at 75 and above	24 (brittle fracture)
EMMA (C-254-1C in tension)		
1-yr	175	167
2-yr	150	170
3-yr	Brittle fracture at 75 and above	163
5-yr	Brittle fracture at 75 and above	16 (brittle fracture)
UV/HUMIDITY (C-254-1C in tension)		
1-yr	150	174
2-yr	225	235
3-yr	260	267
5-yr	325	315
10-yr	375	336
LAB. AGED CONTROL		
GR212 in tension	350	317
C-254-1C in tension	175	174
TEMP/HUMIDITY (C-254-1C in tension)	175	167

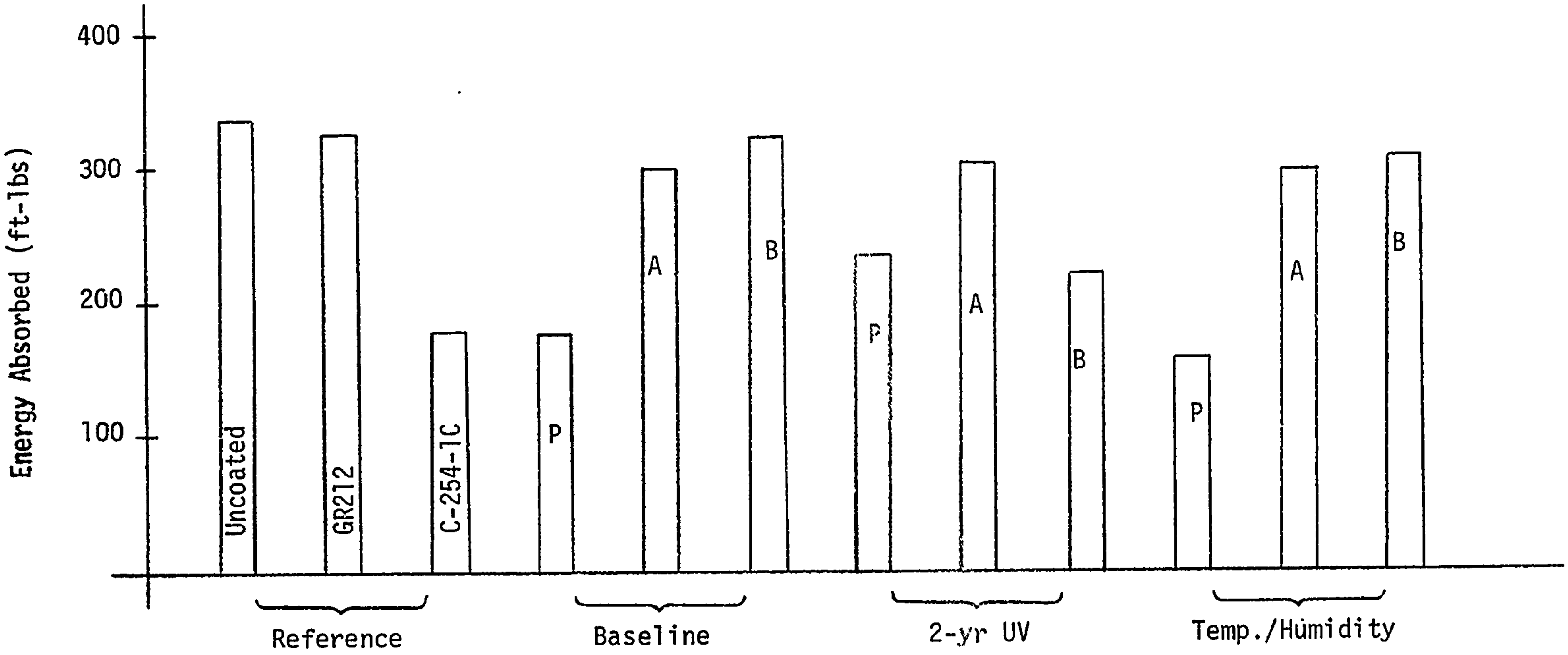


Figure 34. MTS Flexural Beam Tests - Average Data Summary.

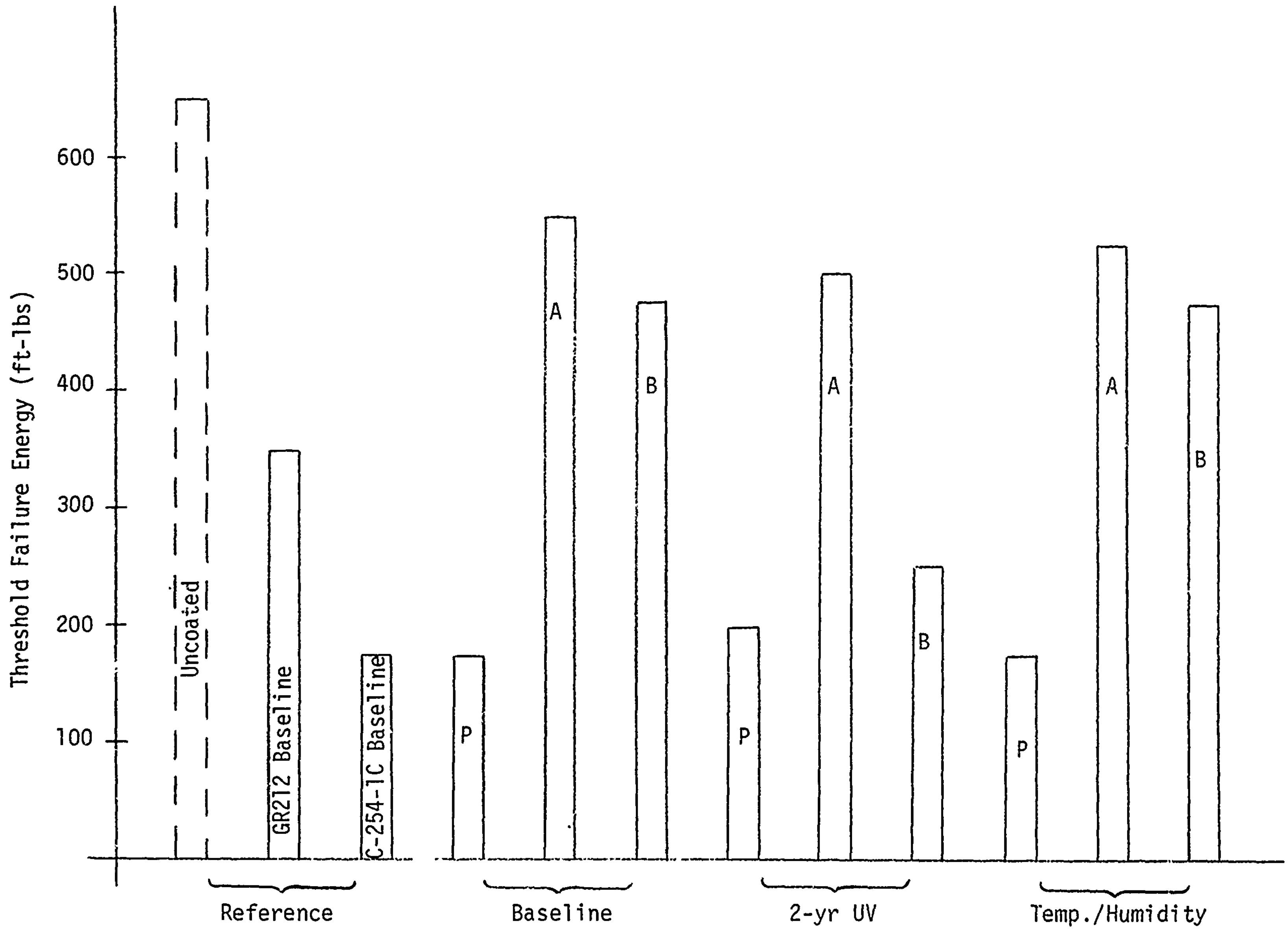


Figure 35. Falling Weight Beam Tests - Threshold-of-Failure Summary.

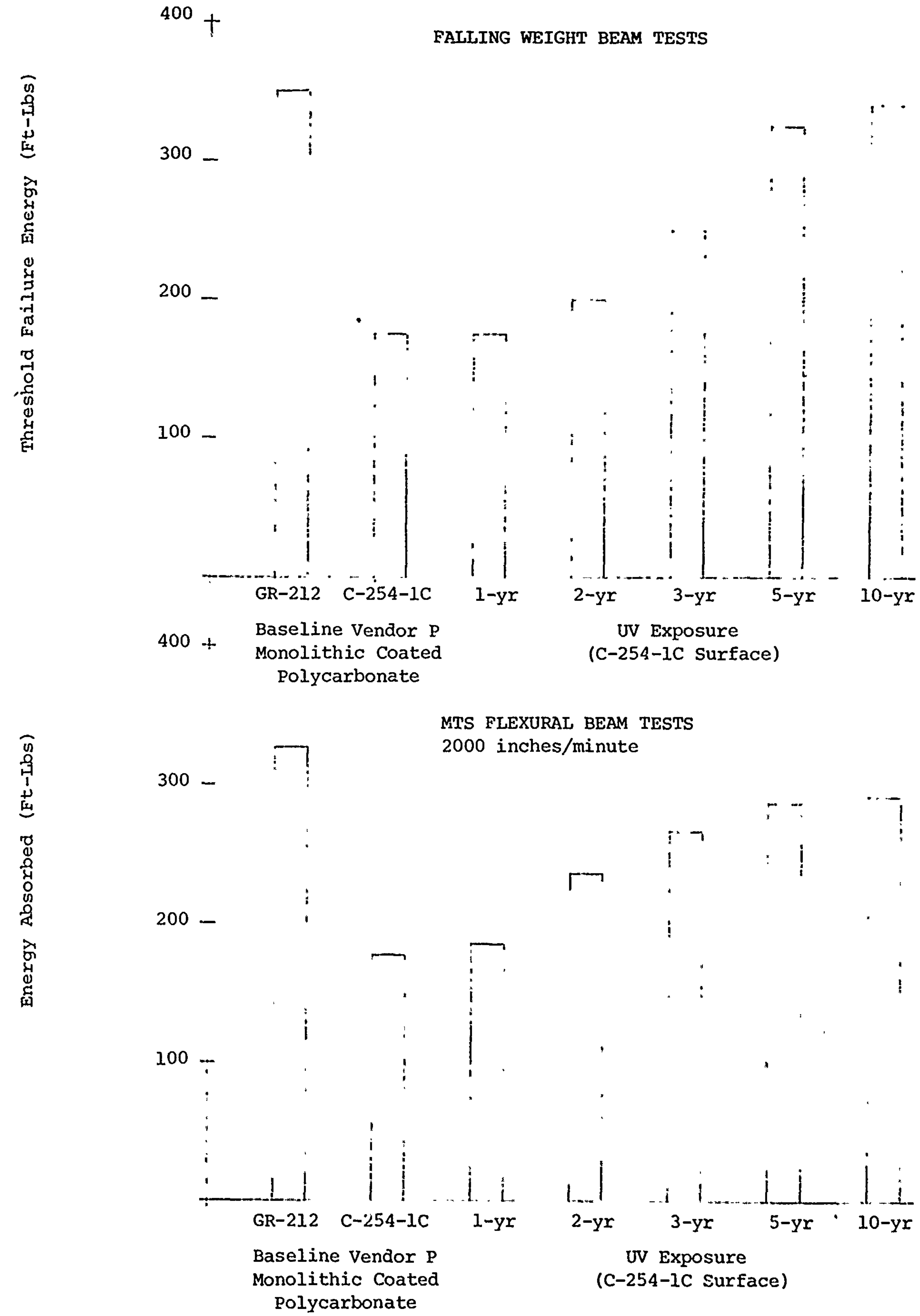
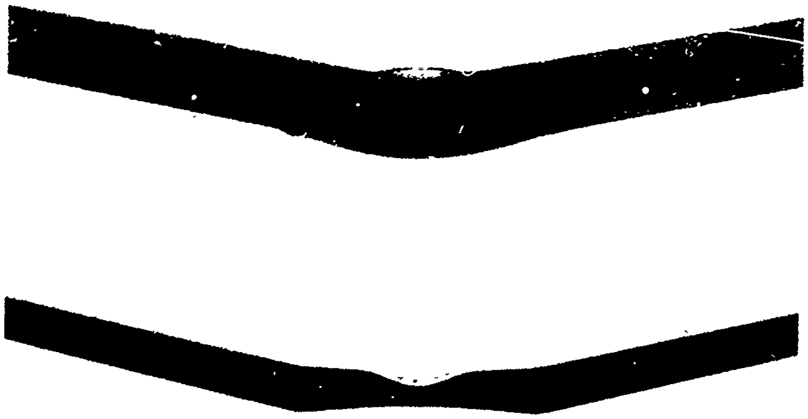
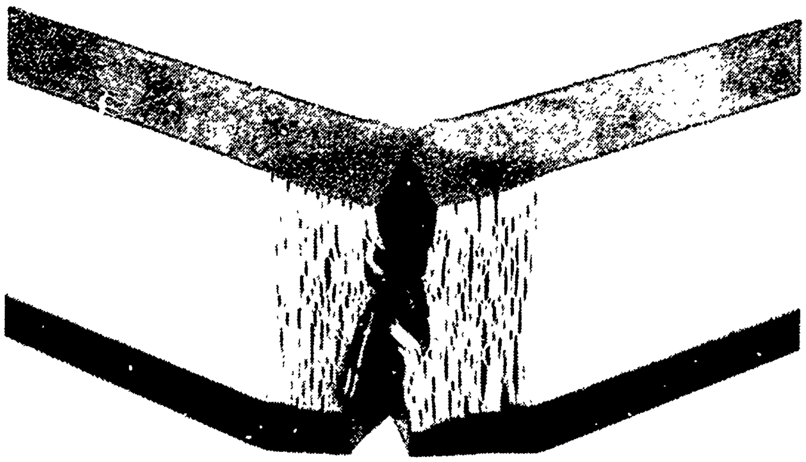


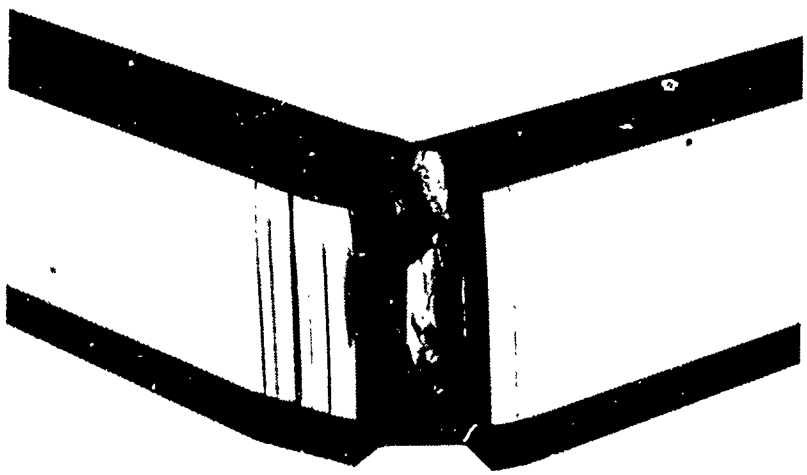
Figure 36. Effect of Laboratory Accelerated Ultraviolet Radiation Exposure.



Vendor A



Vendor B



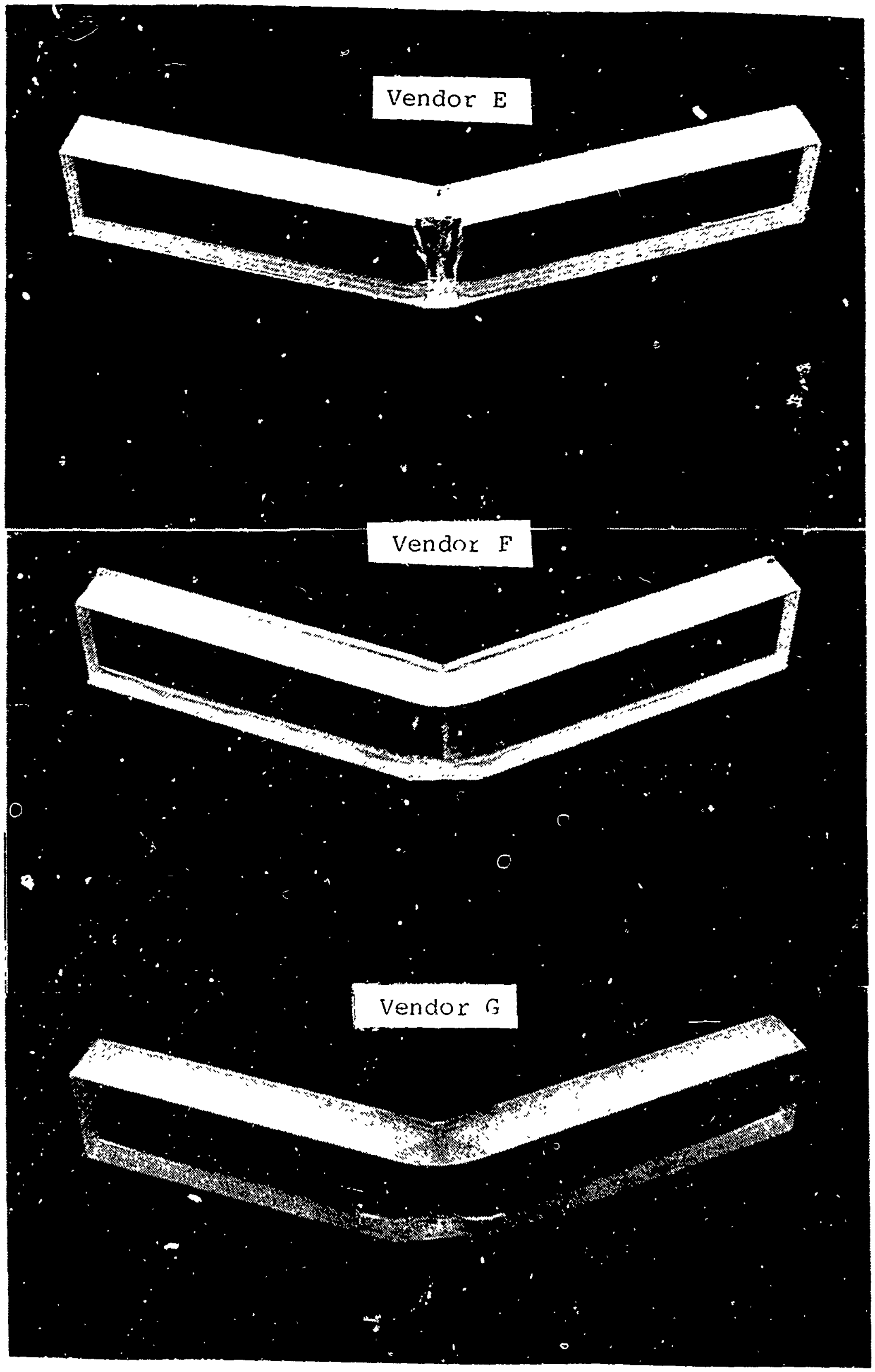
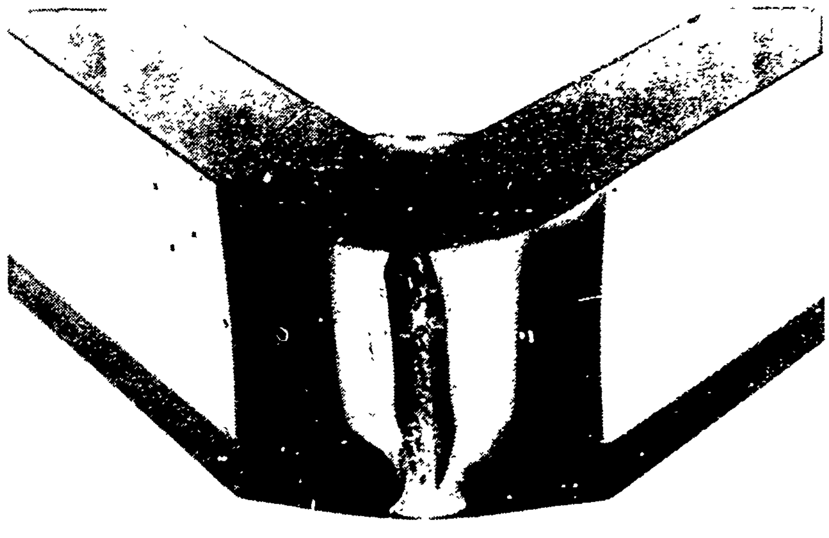
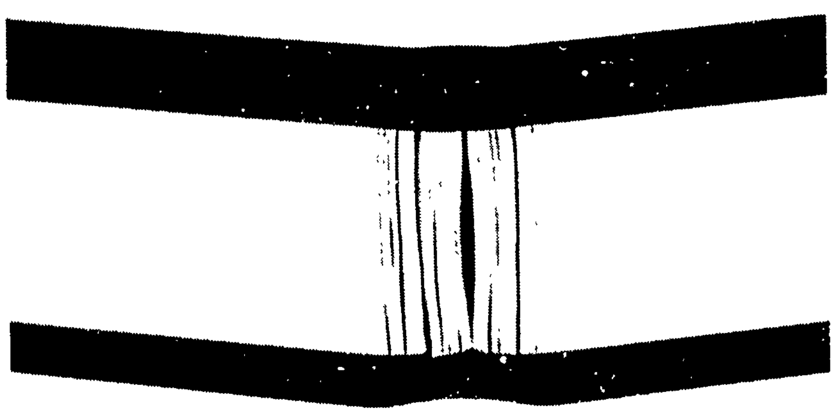


Figure 38. Typical MTS Laminated Beam Specimens after Test.



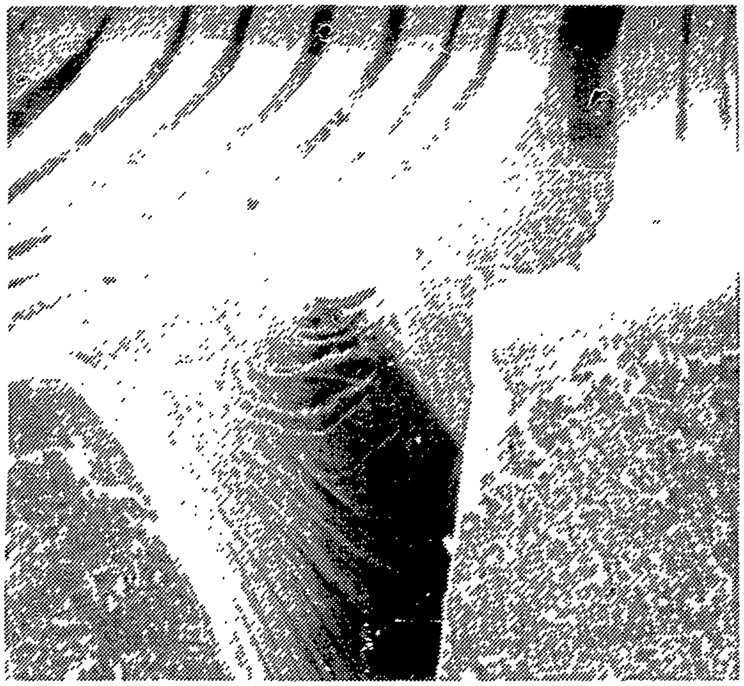
Vendor A

Vendor B



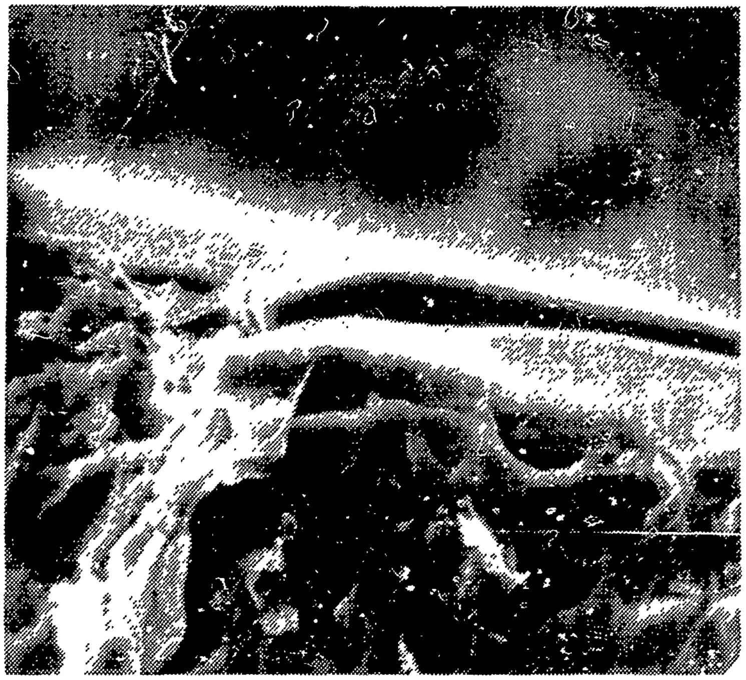
Vendor P

Figure 39. Typical Failed Falling Weight Beam.



100 X

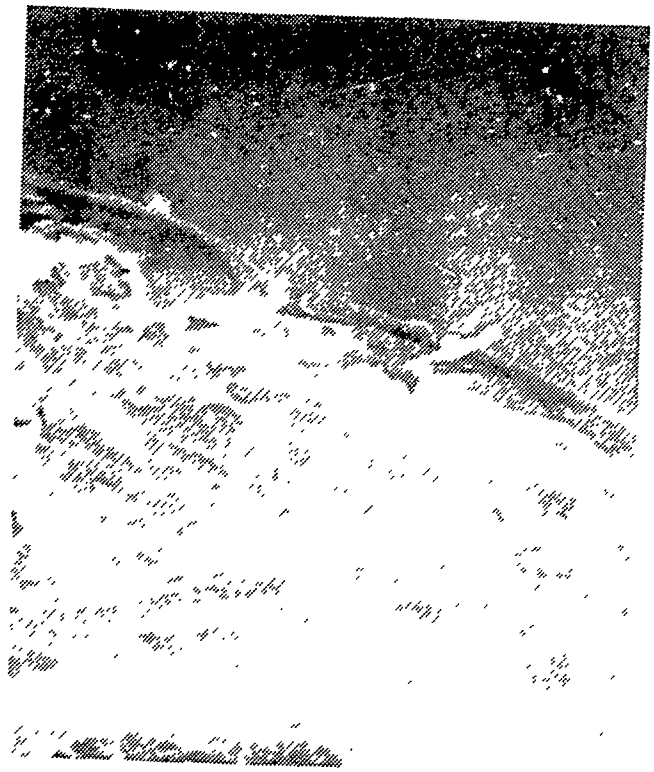
Figure 40. Fissure Opening - Vendor P Beam.



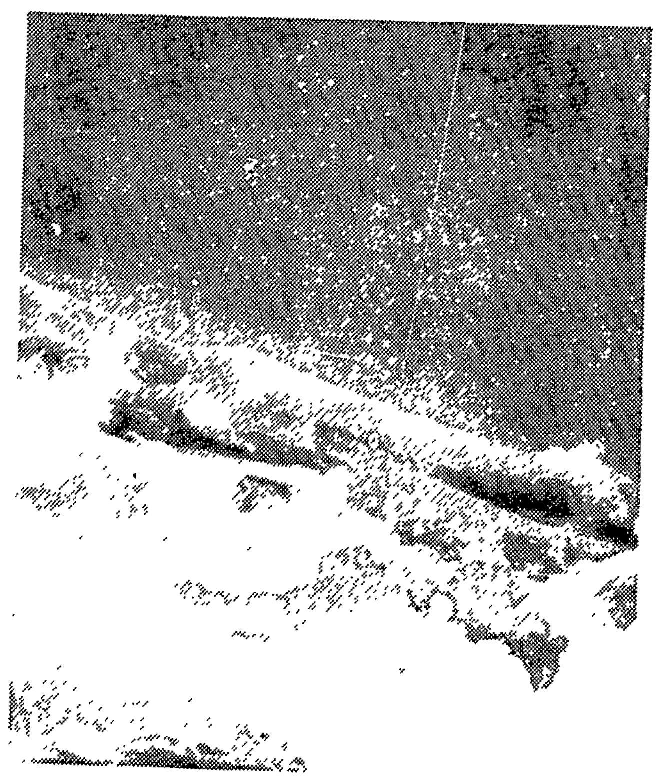
300 X

1000 X

Figure 41. Cross Section of C-254-1C Coating.



300 X

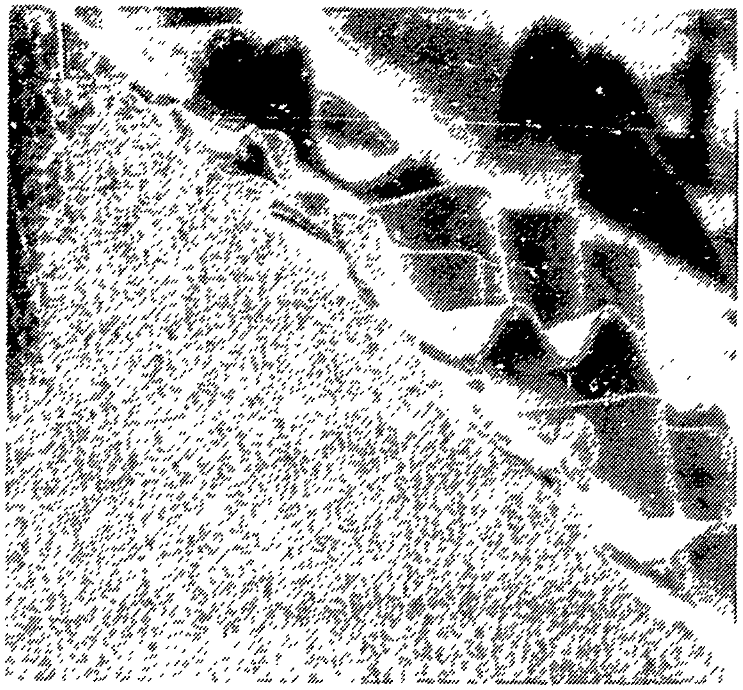


1000 X

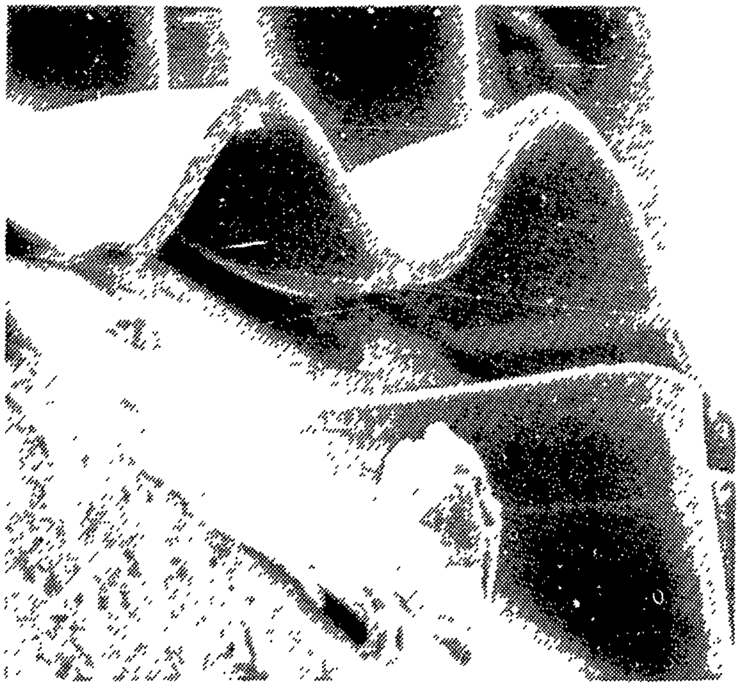
Figure 42. Cross Section of Vendor A Coated Surface.

1,000 X

Figure 43. Vendor B Coated Surface.



100 X



300 X

Figure 44 Cross Section of Vendor B Coated Surface.

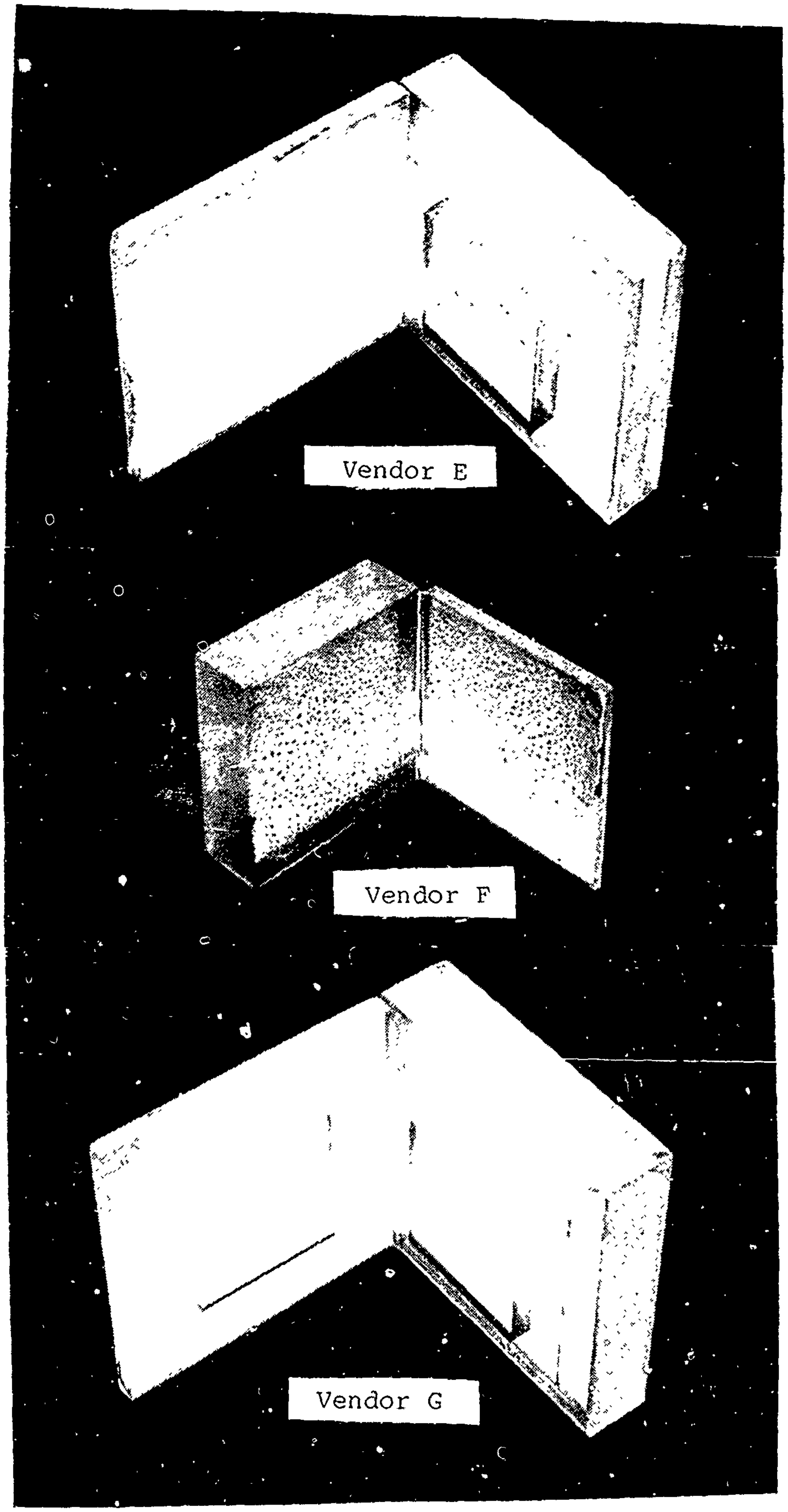


Figure 45 Typical Failed Flatwise Tension Specimens

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Differences in behavior of the candidate canopy materials, when subjected to the selected test conditions, can be determined directly by comparing the experimentally generated data presented in Paragraph 7 of Section II and summarized in Section III. It is significant to note the following:

(i) The impact resistance of coated monolithic polycarbonate is considerably less than that of uncoated polycarbonate even when the coatings used are extremely thin.

(ii) The material behavior of coated monolithic polycarbonate is influenced by ultraviolet radiation.

(iii) Test samples of coated monolithic polycarbonate exposed to accelerated outdoor sunshine (EMMA and EMMAQUA) at DSET Laboratories showed splotches of coating removal after simulated two year conditioning. After simulated three and five year exposure additional coating loss was evident, and a complete loss of ductility resulted in brittle fractures of all beams tested at low energy levels.

(iv) Resultant test data for all laminated samples tested was influenced by the interlayer configuration (silicone or urethane).

It is recommended that future in-depth investigations be made in an attempt to:

(i) correlate natural versus accelerated and real-world versus laboratory environmental exposures;

(ii) determine effects on impact resistance from combining unavoidable surface scratches from cleaning with environmental exposure conditions; and

(iii) identify durability test deficiencies and define testing procedures for transparency development which reflect the in-service experience of operational Air Force aircraft.

APPENDIX A

RAIN EROSION EVALUATION AND ANALYSIS OF F16-AIRCRAFT CANOPY COATINGS

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RAIN EROSION EVALUATION AND ANALYSIS OF F-16 AIRCRAFT CANOPY COATINGS

Introduction

An evaluation study of the relative rain erosion resistance of production and potential candidate coating materials for the F-16 aircraft polycarbonate canopy was conducted. This study was requested at the behest of the University of Dayton Research Institute and the Air Force F-16 Systems Program Office. This work was conducted between July 1980 and September 1980.

The objective of this program was to determine rain erosion resistance of three canopy coatings hereinafter referred to as F-16 Production Coating, (Vendor P), Vendor A Coating and Vendor B Coating.

Test Procedures

The as-received specimens were numbered and logged according to the standard procedure for the test apparatus. All specimens were visually inspected, cleaned and weighed prior to rainfield exposure. Post-test analysis included visual inspection of percent coating removal, hazemeter measurements and scanning electron microscopic analysis.

Rain Erosion Test Description and Conditions

(a) Mach 1.2 Rain Erosion Test Apparatus

The variable speed (up to Mach 1.2) rotating arm facility consists of an eight-foot diameter double arm propeller blade mounted horizontally and powered by a 400 hp motor. A pipe with hypodermic type needles is positioned to spray controlled water droplets (2.0 mm dia.) on the specimens which are inserted in the blade tips. A stroboscopic unit and closed

circuit television camera enable observation of the specimen during testing. End point is the failure of the coating to the substrate or damage of the substrate. This test apparatus is fully described in AFML-TR-70-240. See Figure A-1.

(b) Test Conditions for Coated Polycarbonate Specimens

For the purposes of this particular evaluation study, matched pairs of specimens were inserted into specimen holders at a 30° angle of incidence to the rain droplet impact. All testing was conducted at 500 mph. Duration of the tests was established at 1, 2, 5, 10 and 15 minute intervals.

Rain Erosion Test Results

(a) Visual Examination - No UV Accelerated Weathering

Visual examination of the coated polycarbonate specimens showed initiation of coating removal from the F-16 Production coated specimens occurred during the interval between two and five minutes of rainfield exposure. Vendor A Coating showed initiation of coating removal in the interval between five and 10 minutes of rainfield exposure. Vendor B Coating showed pitting, but no coating removal after 15 minutes of rainfield exposure. The results of all tests are tabularized in Tables A-1 through A-3. The worst case data is shown in Figure A-2.

(b) Visual Examination-1 Year Simulated UV Accelerated Weathering

The F-16 Production Coating showed initiation of coating removal during the 0 to 1 minute interval of rainfield exposure. Vendor A Coating showed increased coating removal in the five to 10 minute interval of rainfield exposure. Vendor B Coating showed severe pitting of the coating surface at the 15 minute interval, but no observable coating removal. The results of these tests are tabularized in Tables A-4 through A-6. The worst case data is shown in Figure A-3.

(c) Visual Examination-3 Year Simulated UV Accelerated Weathering

The F-16 Production Coating showed initiation of increased coating removal in the 0 to 1 minute interval of

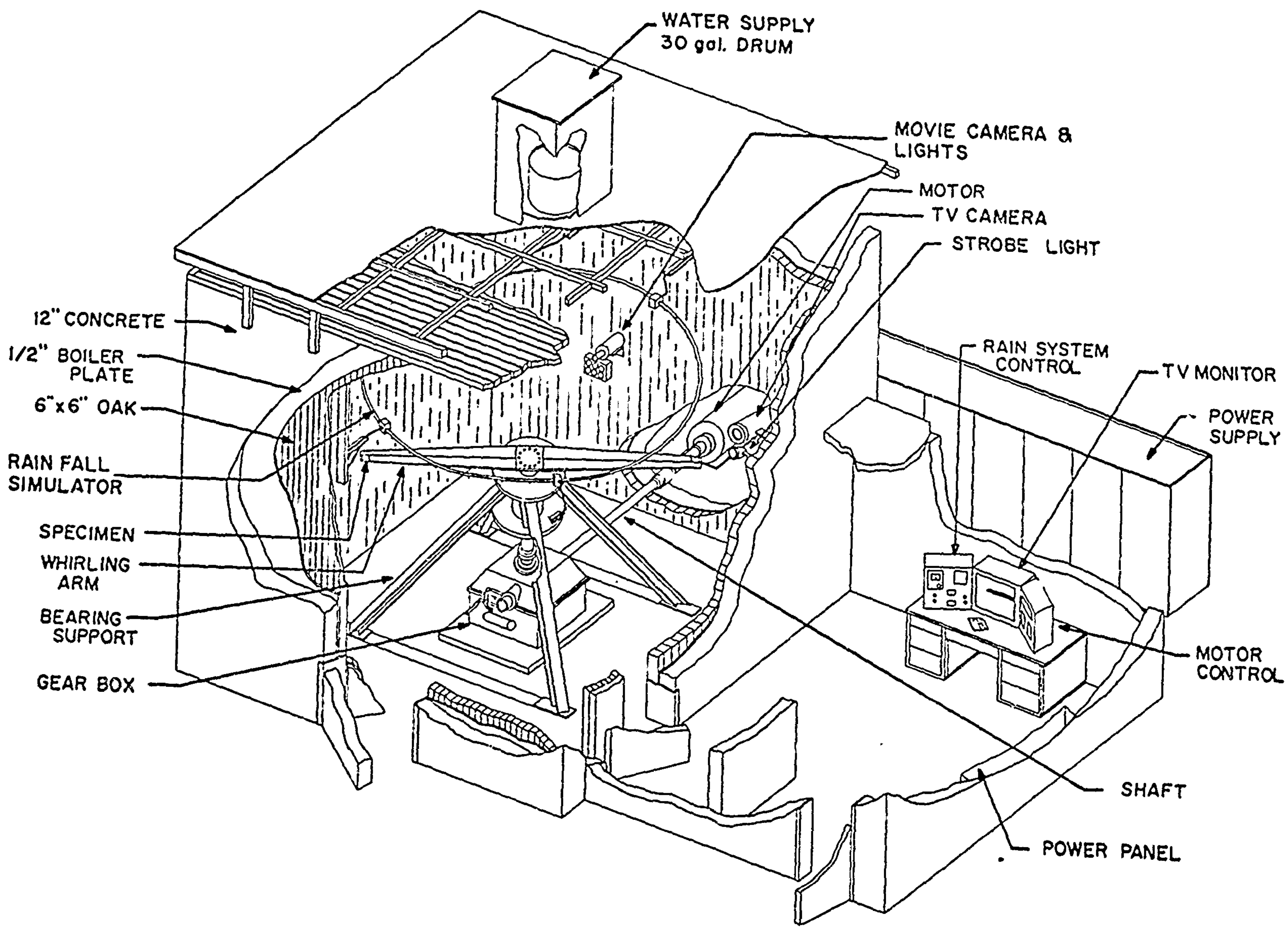

Figure A-1. AFML Rotating Arm Apparatus.

TABLE A-1

F-16 PRODUCTION COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH   RAINFALL: 1 IN/HR

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11289	PX26	1.0	+.0005	Surface Scratch
11290	PX27	1.0	+.0016	Surface Scratch
11295	PX51	2.0	.0001	Surface Pitting
11296	PX52	2.0	.0012	Surface Pitting
11291	PX28	5.0	.0051	60% Coating Removal
11292	PX29	5.0	.0053	60% Coating Removal
11293	PX30	10.0	.0059	90% Coating Removal
11294	PX50	10.0	.0073	90% Coating Removal
11299	PX4	15.0	.0071	95% Coating Removal & Substrate Pitting
11300	PX5	15.0	.0176	95% Coating Removal & Substrate Pitting
11297	PX1	30.0	.0008	100% Coating Removal
11298	PX2	30.0	.0001	100% Coating Removal

+ indicates a weight gain after evaluation

TABLE A-2

VENDOR A COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH   RAINFALL: 1 IN/HR

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11305	AX5	1.0	.0000	No Visible Damage
11306	AX6	1.0	.0012	Surface Scratch
11311	AX29	2.0	+.0001	Slight Damage
11312	AX30	2.0	.0000	No Visible Damage
11307	AX25	5.0	.0008	Surface Scratches
11308	AX26	5.0	.0006	Surface Scratches
11309	AX27	10.0	.0018	Slight Damage
11310	AX28	10.0	.0016	20% Coating Removal
11313	AX49	15.0	.0058	50% Coating Removal
11314	AX50	15.0	.0011	Coating Edge Removal

TABLE A-3

VENDOR B COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH   RAINFALL: 1 IN/HR

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11325	BX3	1.0	.0005	No Visible Damage
11326	BX4	1.0	.0007	Surface Scratch
11331	BX27	2.0	.0005	Surface Scratch
11332	BX28	2.0	.0002	No Damage
11327	BX5	5.0	.0010	Surface Scratch
11328	BX6	5.0	.0004	Small Pits
11329	BX25	10.0	.0009	No Damage
11330	BX26	10.0	.0008	Scratches & Pits
11333	BX29	15.0	.0003	Scratches & Pits
11334	BX49	15.0	.0016	Scratches & Pits

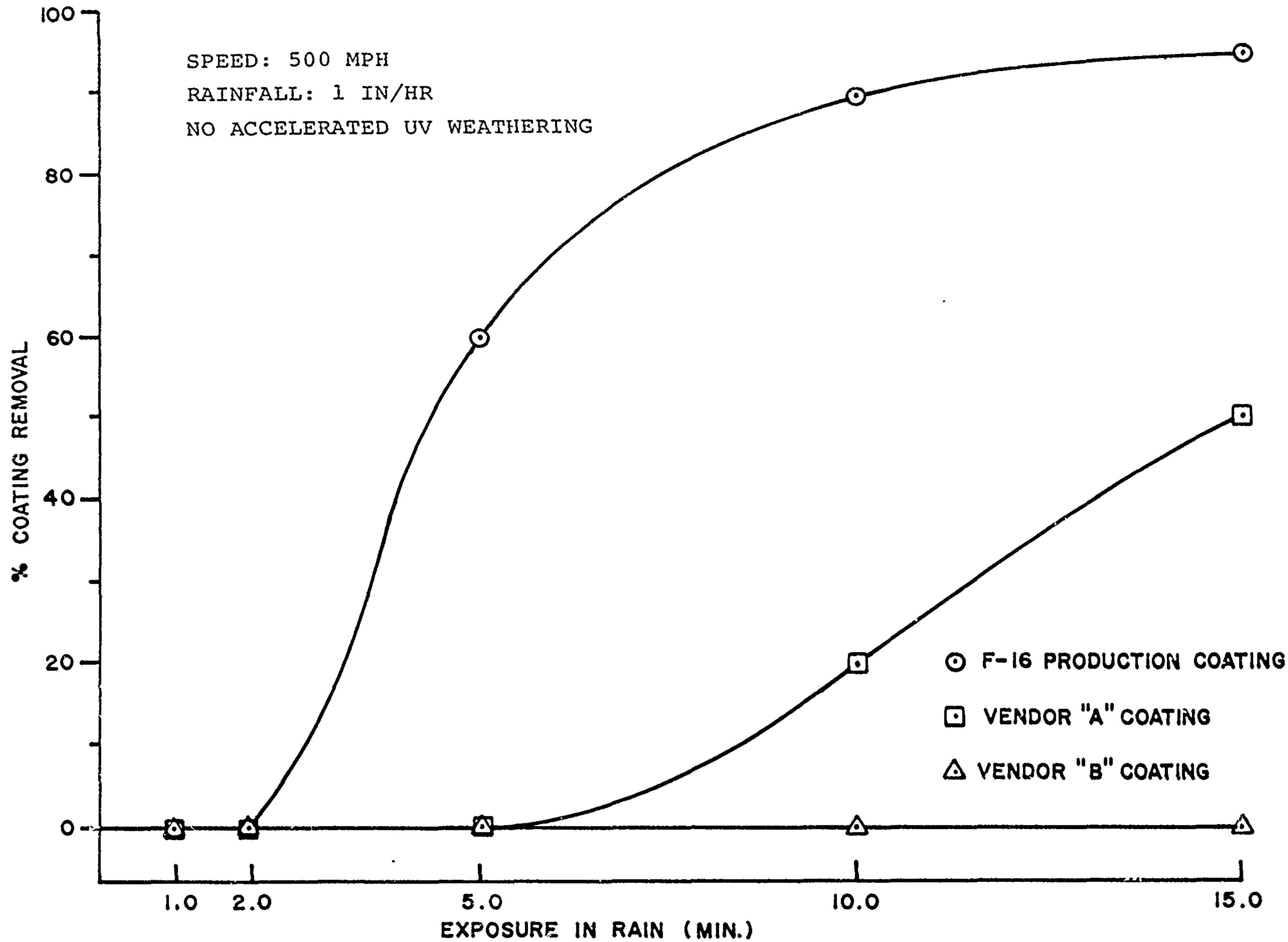

Figure A-2. Percent Coating Removal vs. Time in Rain at 500 MPH

TABLE A-4

F-16 COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH RAINFALL: 1 IN/HR

1 YEAR SIMULATED UV EXPOSURE

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11510	PX9	1.0	.0012	1% Coating Removal
11511	PX10	1.0	.0006	No Damage
11512	PX11	2.0	.0018	5% Coating Removal
11513	PX12	2.0	.0018	15% Coating Removal
11520	PX53	5.0	.0062	80% Coating Removal
11521	PX55	5.0	.0066	95% Coating Removal
11516	PX33	10.0	.0073	100% Coating Removal
11517	PX34	10.0	.0099	100% Coating Removal
11518	PX35	15.0	.0084	100% Coating Removal
11519	PX36	15.0	.0089	100% Coating Removal

TABLE A-5

VENDOR A COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH   RAINFALL: 1 IN/HR

1 YEAR SIMULATED UV EXPOSURE

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11384	AX9	1.0	.0003	Surface Scratches
11385	AX10	1.0	+.0009	Minor Pitting
11386	AX11	2.0	.0004	Scratches
11387	AX12	2.0	.0007	Scratches & Edge Removal
11388	AX31	5.0	.0018	Surface Scratches
11389	AX32	5.0	.0005	Surface Scratches & Edge Damage
11390	AX33	10.0	.0055	50% Coating Removal
11391	AX34	10.0	.0012	No Damage
11392	AX35	15.0	.0008	Coating Edge Removal
11393	AX36	15.0	.0066	70% Coating Removal

TABLE A-6

VENDOR B COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH RAINFALL: 1 IN/HR

1 YEAR SIMULATED UV EXPOSURE

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11454	BX7	1.0	.0020	No Damage
11455	BX8	1.0	.0012	Slight Pitting
11456	BX9	2.0	.0017	No Damage
11457	BX10	2.0	.0015	No Damage
11458	BX11	5.0	.0009	Slight Pitting
11459	BX12	5.0	.0011	Slight Pitting
11460	BX31	10.0	.0005	Pitting
11461	BX32	10.0	.0019	Pitting
11465	BX36	15.0	.0028	Severe Pitting
11466	BX53	15.0	.0034	Severe Pitting
11467	BX54	15.0	.0020	Severe Pitting

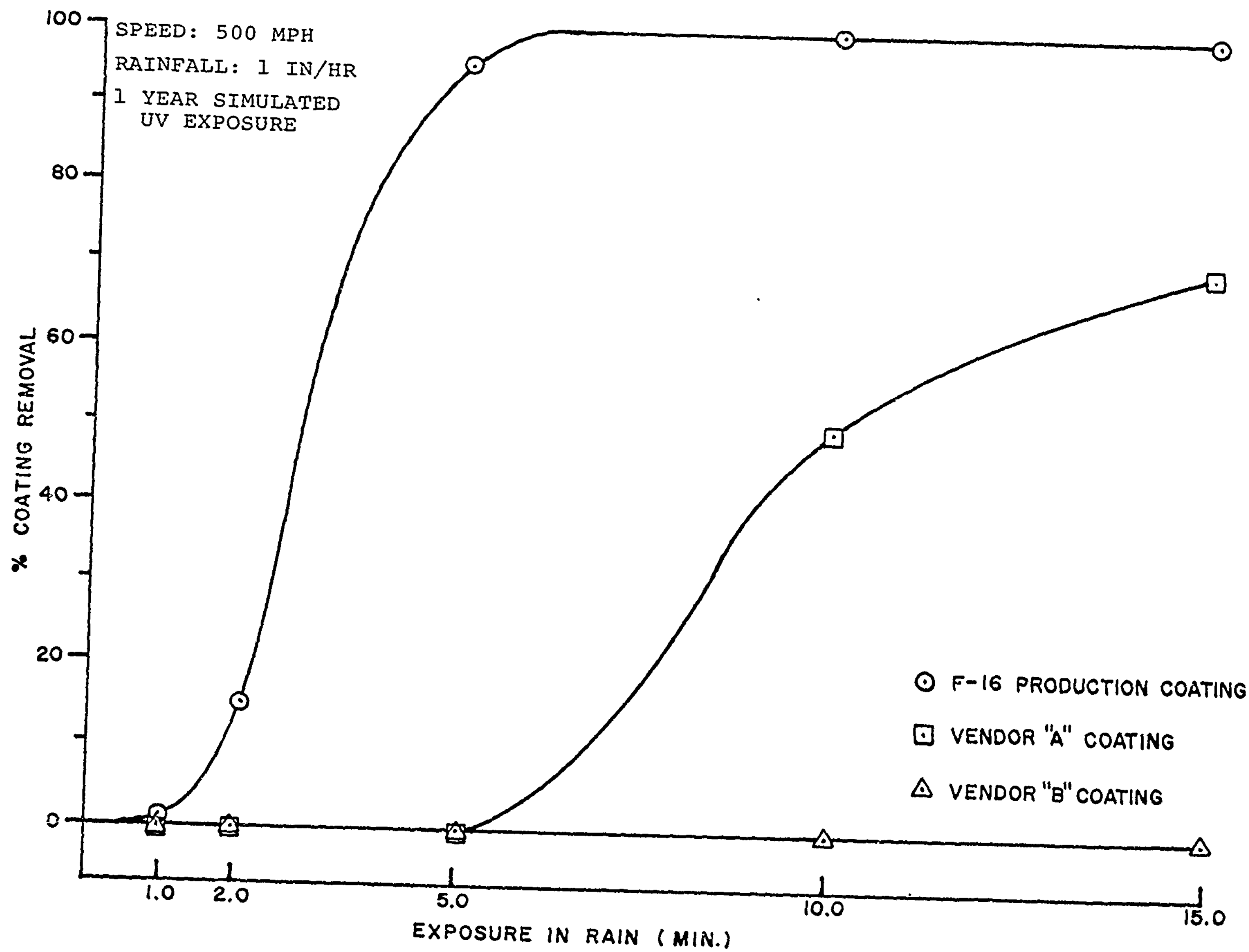

Figure A-3. Percent Coating Removal vs. Time in Rain at 500 MPH

rainfield exposure. Vendor A Coating continued to show the initiation and percent of coating removal at the five to 10 minute interval of rainfield exposure. Vendor B Coating showed severe pitting of the coating surface at the 15 minute interval, but no observable coating removed. The results of the tests are tabularized in Tables A-7 through A-9. The worst case data is shown in Figure A-4.

(d) Visual Examination - Desert Exposure (DSET Laboratories)

The F-16 Production Coating subjected to EMMA and EMMAQUA tests in the desert indicate an increased coating removal at the five minute interval of rainfield exposure as compared to the same interval of rainfield exposure for the three year UV accelerated weathering specimens. The results are shown in Table A-10.

(e) Weight Loss Measurements

For the purposes of this evaluation study, weight loss measurements were ineffective as an indicator and were further complicated by calcium carbonate deposits on the specimens. Deposits were the result of evaporation of hard water droplets from the rain simulation system.

(f) Transmittance Measurements

Haze and transmittance measurements were insensitive indicators to evaluate rain erosion resistance of the canopy coatings. Due to the calcium carbonate deposits and the type of failure involved, these measurements were terminated early in the program.

(g) Scanning Electron Microscopy

Scanning electron microscopy proved to be a highly useful tool for assessing the damage mechanisms. The following is a brief interpretation of the electron microscopic evidence.

Under magnification of 100X to 1000X, the F-16 Production Coating evidenced areas of nonuniform adhesion to the polycarbonate substrate. The rapid failure of this coating was

TABLE A-7

F-16 COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH   RAINFALL: 1 IN/HR

3 YEAR SIMULATED UV EXPOSURE

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11550	PX43	1.0	.0001	No Damage
11551	PX44	1.0	.0004	10% Coating Removal
11552	PX45	2.0	+.0013	Pitting
11553	PX46	2.0	.0003	Pitting
11506	PX41	2.0	.0007	5% Coating Removal
11507	PX42	2.0	.0018	2% Coating Removal
11498	PX15	2.0	+.0005	3% Coating Removal
11499	PX16	2.0	.0000	3% Coating Removal
11502	PX37	10.0	.0091	95% Coating Removal
11503	PX38	10.0	.0000	No Damage
11500	PX17	15.0	.0070	100% Coating Removal and Substrate Pitting
11501	PX18	15.0	.0064	100% Coating Removal and Substrate Pitting

TABLE A-8

VENDOR A COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH   RAINFALL: 1 IN/HR

3 YEAR SIMULATED UV EXPOSURE

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11472	AX15	1.0	.0004	Minor Pitting
11473	AX16	1.0	.0001	Minor Pitting
11556	AX19	2.0	.0001	Coating Edge Removal
11557	AX20	2.0	+.0005	Coating Edge Removal
11474	AX17	5.0	.0000	No Damage
11475	AX18	5.0	.0003	No Damage
11558	AX21	10.0	.0048	50% Coating Removal
11559	AX23	10.0	.0004	Coating Edge Removal
11560	AX43	15.0	+.0003	Coating Edge Removal
11561	AX44	15.0	.0071	70% Coating Removal

TABLE A-9

VENDOR B COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH   RAINFALL: 1 IN/HR

3 YEAR SIMULATED UV EXPOSURE

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11484	BX15	1.0	.0002	Minor Pitting
11485	BX16	1.0	.0004	Minor Pitting
11490	BX39	2.0	.0008	Pitting
11491	BX40	2.0	.0007	Pitting
11486	BX17	5.0	.0011	Pitting
11488	BX37	5.0	.0006	Pitting
11492	BX41	10.0	.0055	Severe Pitting
11493	BX42	10.0	.0052	Severe Pitting
11494	BX70	15.0	.0042	Severe Pitting
11495	BX71	15.0	.0054	Severe Pitting

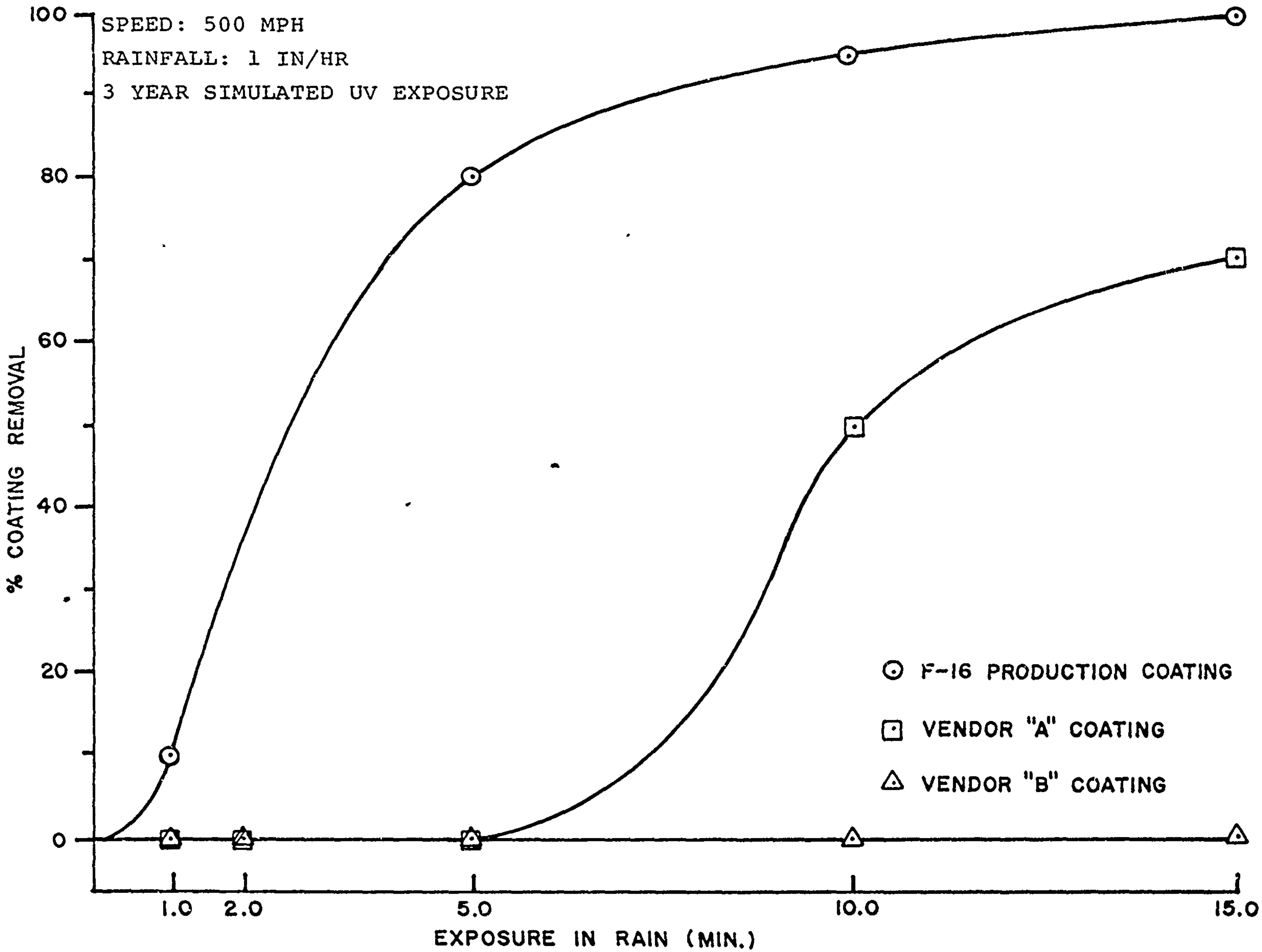

Figure A-4. Percent Coating Removal vs. Time in Rain at 500 MPH.

TABLE A-10

F-16 COATED POLYCARBONATE
RAIN EROSION EVALUATION

SPEED: 500 MPH RAINFALL: 1 IN/HR

3-YEAR DESERT EXPOSURE

Specimen No.	UD ID	Exp Time	Weight Loss (gm)	Remarks
11342	KX6	1.0	.0014	5% Coating Removal
11343	KX7	1.0	.0013	2% Coating Removal
11359	KX1	5.0	.0065	80% Coating Removal
11360	KX4	5.0	.0046	70% Coating Removal
11361	KX12	1.0	.0014	Surface Pitting
11362	KX14	1.0	.0014	Surface Pitting

induced by a lack of good adhesion and not a typical erosion failure. Photographic evidence shows no residual coating material in the areas where significant percentages of the coating were removed. Surface cleanliness of the polycarbonate before coating application is suspect.

Under similar magnifications, the Vendor A Coating also showed areas of nonuniform adhesion to the polycarbonate substrate. A major finding was the significant amount of debris in the form of fibers and possible oils present at the interface of the coating to the substrate. The foreign objects in the coating contributed in part to the premature failure of this coating. The cleanliness of application at the Vendor A site is of concern.

Vendor B Coating, under scanning electron microscopy, evidenced pitting and cratering of a classic erosion phenomena. Examination of the coating showed no evidence of debris. Examination of the pits and craters showed good adhesion and coating integrity.

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